A Generic Protocol For An Integrated Land Information System In Humid Subtropical Highlands: A Case Study In Yunnan Province, China

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A GENERIC PROTOCOL FOR AN INTEGRATED LAND INFORMATION SYSTEM IN HUMID SUBTROPICAL HIGHLANDS: A CASE STUDY IN YUNNAN PROVINCE, CHINA

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Abstract

This study develops a basis for a land information system for the 40 ha subtropical highland catchment of Wang Jia, Yunnan Province, China. Information, including meteorology, geology, geomorphology, biology, pedology and crop productivity, was integrated using a geomorphopedological approach and expressed as maps using GIS. The developed protocol is proposed as a generic system, applicable to agricultural land evaluation in subtropical highland catchments.

The results demonstrate that Wang Jia Catchment is relatively representative of the region, in terms of geomorphological features and land cover. Catchment soils, developed from residual, colluvial and alluvial materials of sandstone, shale and dolomite on different landscapes, were still young and strongly influenced by their geological parent material. Soils were normally slightly acidic to neutral. Soil fertility varied from poor to very fertile. Maize yield was significantly correlated with soil pH, total N, available N, P and K and thus the Soil Fertility Index. In 2002, maize yield was significantly correlated with manure and urea applications.

There was considerable potential to increase maize yield with modified and innovative cropping practices in the catchment. Adopted primarily as a soil conservation practice, contour cultivation did not increase maize yield compared to downslope cultivation. Polythene mulch tended to increase maize yield in most years. These results largely accord with the results from controlled research plots in the same catchment.

Analysis of intra-plot variations showed that soil samples from planting pits had higher total soil organic matter, total N, available N, available P and available K than inter-row samples, but with higher standard deviations. Most soil fertility parameters for inter-row samples were more similar to traditional random composite samples. These results suggest if composite samples were taken only from inter-rows, the results would have been similar, but the risk of sampling error would have been reduced.

The land information system established in this study is suitable for designing, evaluating and monitoring sustainable agricultural practices central to soil conservation and crop yield improvement and thus contributing to decision-making for sustainable agricultural land management in this region.

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Table of contents

List of Figures

List of Tables

List of Plates

Chapter 1. Introduction and Literature review

General aim

This project aims to collect baseline information and build up an integrated land information system for a subtropical highland agricultural catchment in Yunnan Province, Southwest China. Wang Jia Catchment has been selected as the test catchment in this mountainous region. Geological, geomorphological and pedological surveys have been conducted in the catchment in parallel with developing strategies for land use changes and substantial relevant information was integrated to establish a land information system using Geographical Information System (GIS). This information system can provide the baseline information for the catchment before the land use changes and can be used to follow up the effects of land use changes afterwards. As a reference system for land use evaluation and the evaluation of the selected soil conservation practices, this information can also serve for decision-making for sustainable land management.

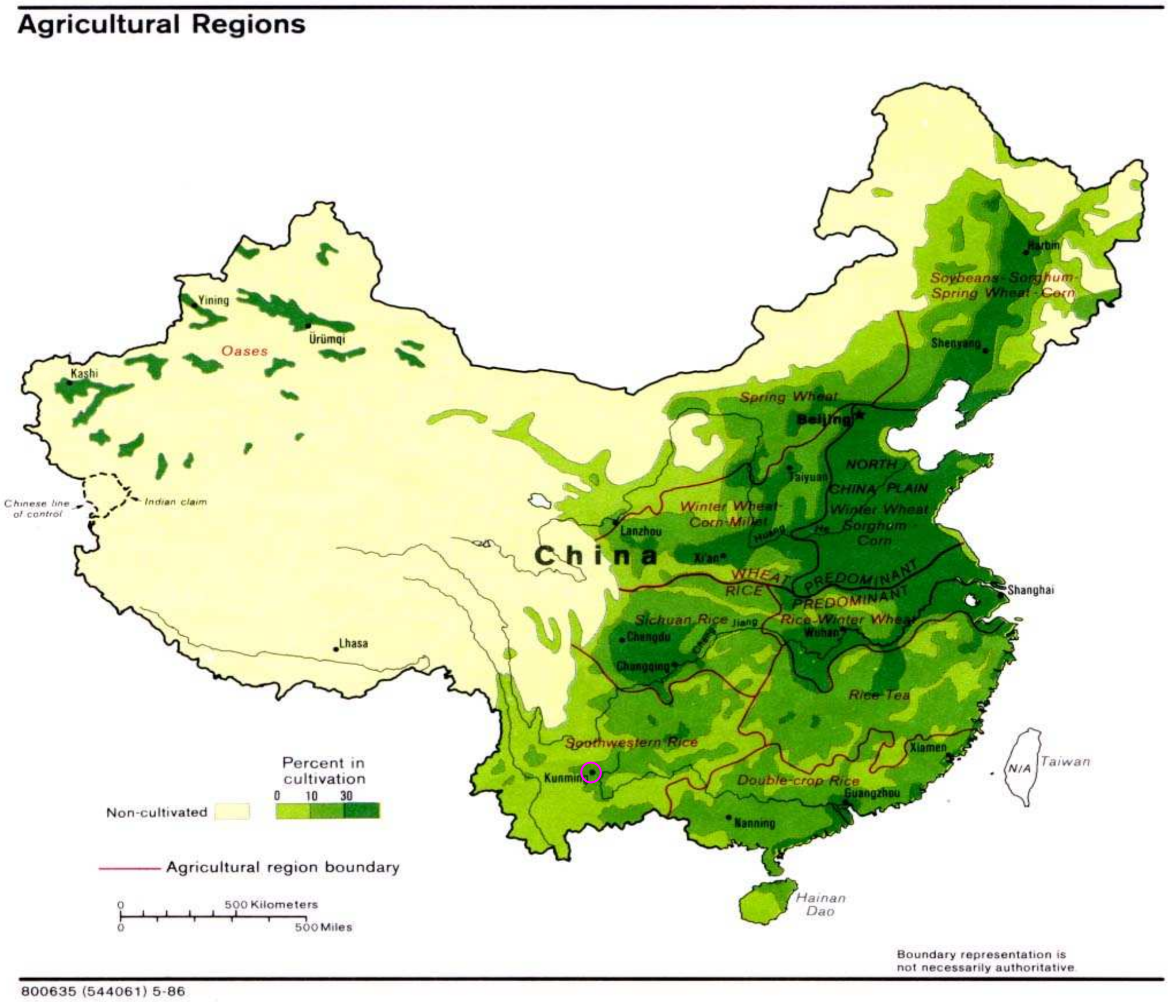
Previous work found that agricultural land in this region faces extreme pressures from economic development, especially on sloping land (Fullen *et al.*, 1999a). The more extensive cultivation, unsuitable land use and inappropriate cropping practices cause serious soil erosion, which in turn causes land degradation and deterioration in soil fertility and soil physical properties. The effective measures for soil conservation and crop yield improvement, developed in runoff plots or identified from indigenous knowledge, were recommended and implemented in farmer-managed plots in the catchment. One hundred plots were selected for crop survey, in which 30 plots received more detailed soil survey.

This research programme is part of a larger project (sustainable highland agriculture in Southeast Asia: SHASEA) funded by the European Union (Contract No. ERBIC18CT980326). The aim of this project was to increase, in a sustainable and environmentally friendly way, the productivity of maize, wheat and soybean grown on hill slopes. The twin goals of increased productivity and sustainability were achieved by the development and implementation of a land management plan that included mechanical and agronomic measures and soil management techniques designed to be more sustainable than existing practices. The research reported here comprizes the baseline information survey for the design of land management systems.

1.1 Pressures on China's agricultural land

China has an area of 9.6 million km^2, extending from ~22-55^{o}N and 78-135^{o}E. Among its territory, unusable land, such as desert, glaciers, stone mountains and cold highland is >35%. China's extensive mountainous and hilly topography constrains agriculture. According to the data of the Second National Soil Investigation, 70% of the land in China is mountains and hills (Wang, 1992). The cultivated land area covers 131.1 million hectares, which represents 12% of national territory and occupies 7% of the world's arable land (Wen, 1993; Fischer *et al.*, 1998). Furthermore, the productive land resources are severely restrained by climate. Much of western China is too arid or too cold for extensive crop production (Zhao, 1986). Cultivated lands are mainly in the east and central humid areas (Figure 1.1).

Figure 1.1. Agricultural Regions in China



1.1.1 Pressure from increasing population: The total population in China is 1,290 million, which is the highest of any country and is 22% of world population. Despite the slowing of China's growth rate, owing to family planning policy, China's population is still increasing. China's population increased from 556.7 million in 1950 to 1,290 million in 2000 (China State Statistical Bureau, 2001). Over 56% of the population reside in mountainous areas (Wang *et al.,* 1999). China still has a very high percentage of people on low incomes, and at least 60% are dependent on rural livelihoods (Cannon, 2000). Agriculture is still their main activity and comprizes their main income. Before 1990, the agricultural population was 84% (Chen, 1990). In 1998, ~75% of the labour force were engaged in agriculture and the livelihoods of most of the population depended on agriculture (Duan, 1999).

Despite its large area, China has a very low land resource per capita, at only 0.84 ha, which is 1/3 of the world average. However, only ~14% of its total land area is arable and on a per capita basis is only 40% of the world average (Table 1.1). China's arable land resource is not only limited in quantity but also in quality. The best arable land (i.e. no significant constraints as regards soil type, fertility, slope or climate) accounts for only 40% of the total, 34% has limited constraints, and 23% has significant constraints. About 3% of land used for agricultural production is unsuitable (Li *et al.,* 1997).

Table 1.1. Distribution of land resources (per capita)

Land resources	World mean (ha)	China mean (ha)
Croplands	0.29	0.12*
Forests	0.74	0.12
Grasslands	0.65	0.25
Total	2.47	0.84

*Corrected value based on revised estimated arable land area of 139 m ha.

(Source: Li *et al.,* 1997).

To feed 22% of the world population with only 7% of the world's arable land is a major challenge for Chinese agriculture. Emphasis on maintaining food self-sufficiency exerts additional pressure on the limited land resources and constrains development in rural areas. The population exerts pressure on land use and forced greater cultivation of hill slopes. Although government policy prohibits cultivation of slopes >28% (Barrows, 1982), this limit is breached, to further increase crop production. More care should be given to the sustainable management on these marginal and unsuitable lands. In recent decades, agricultural production increases due to the enhanced use of hybrid seed, fertilizers and pesticide have led to serious environmental problems. Because of the intensification of crop production and resulting depletion of soil fertility, China has become much more dependent on mineral fertilizer use. The mean amount of mineral fertilizer used on farms in China is 379 kg/ha in 1995 (Li *et al.,* 1997).

Most of China's agricultural polices have strongly emphasized food production goals and targets that require intensive use of mineral fertilizers, pesticides, irrigation water and machinery. Because these polices have not been accompanied by incentives for conservation and environmental protection, the natural resource base has deteriorated, particularly in areas with high potential for food production (Li *et al.,* 1997).

1.1.2 Pressure from economic growth: China has been undergoing major economic growth since the 1990s. Economic growth involves the utilization of resources or capital and increasing the output per unit of resources. Natural resources include land. Chinese urbanization and industrialization have taken away substantial amounts of land, especially flat agricultural land. The total urban population was 71.63 million in 1945, but by 1997 increased to 369.89 million (China State Statistical Bureau, 1998). With the expanding urban population, more construction and road building and other facilities are needed and thus more fertile and flat arable land has been occupied. During 1988-1995, there were 980,243 ha of flat land used for city/town construction (China State Statistical Bureau, 1997). Tillage land was reduced greatly, from 1986-1990, by 26.67×10^4 ha per year and from 1991-1994 by 33.3×10^4 ha per year (Qi, 1999). A study in Beijing showed that the tillage land decreased by 11.55×10^4 ha between 1985 and 1995 (Zhu *et al.,* 2001).

Croplands are increasingly affected by pollution mostly arising from industrial discharges of contaminated wastewater or through pollution of irrigation water. Less than 20% of wastewater is treated. So far, 400 million ha of tillage land has been affected, ~2.6 million hectares have been taken out of agriculture and the annual grain foregone is estimated at 5-10 million tonnes. This problem is exacerbated by rapid growth of the rural township and village enterprises, many of which operate at low levels of technical sophistication and generate high pollution levels. About 2 million ha of tillage land were polluted by rural township and village enterprises. Untreated wastewater, mostly urban sewage, is used to irrigate ~1.4 million ha. Acids and heavy metals in this water impair the soil chemistry and in some areas an impervious subsoil hardpan is formed. Studies in Tianjin by the Agricultural Environment Protection Institute over an eight-year period showed 8.4% of wastewater-irrigated farmland produced crops that exceeded safe standards for contaminants (Li *et al.,* 1997).

While development policies have successfully increased food production and industrial output over the past 20 years, it is apparent that this has been achieved at a significant environment cost. Depletion and pollution of water resources, land degradation, soil erosion, loss of biodiversity, desertification and deforestation are now sufficiently widespread that they constrain further economic growth in the agricultural sector. There is evidence of widespread concern about environmental problems among the general public and some government officials, and there is wide-ranging and in many respects adequate legislation. But the desire to regulate and reduce the causes of problems is severely constrained by the overriding emphasis on economic growth. Furthermore, often local officials have interests that are both more narrow and short-term than those that would properly support environmental protection.

1.1.3 Pressure from current farmland tenure: Since the launch of the Household Responsibility System in 1978, arable land was leased to families. Although this system emerged as the dominant national institution in rural China in the early 1980s, further development of this system has been characterized by more diversity, reflecting local conditions since the mid-1980s. Generally, this system generates incentives for production by giving farmers freedom of land use rights and decision-making, linking benefits closely with their performance. The farmer was to fulfil a quota, but was free to choose the producing crops and consume/sell the product. The free market was encouraged and this reform greatly improved production and efficiency.

Although agricultural productivity significantly increased due to these reforms and advanced technology, several dilemmas remain. First, tiny and fragmented farming units emerged as limited farmland was distributed to small individual households. Moreover, farmland parcels differ in terms of soil fertility, irrigation condition and location. In order to distribute land parcels from each grade of land quality, large cultivated land parcels were split, partly used as paths and boundaries. This fragmented structure also limits the possibilities of using relatively advanced mechanical equipment and agricultural infrastructures. The survey data from 7,983 sample villages in 29 provinces illustrate the relatively small plot area, although it has increased in recent years (Table 1.2).

Table 1.2. Area and fragmentation of household land.

Year	Cultivated area per household (ha)	Number of plots per household	Mean size per plot (ha)
1986	0.446	5.85	0.080
1988	0.466	5.67	0.078
1990	0.420	5.52	0.076
1992	0.466	3.16	0.148

(Source: Ministry of Agriculture of China, 1993).

Second, as the population moved (e.g. death, birth and marriage), villages have to readjust the distribution of land to some extent. According to a survey conducted by the Chinese Ministry of Agriculture, since the implementation of the Household Responsibility System in 1978, 65.2% of China's villages readjusted households' land of which 37.1% once, 19.8% twice and 8.3% three times (Kong, 1993). The uncertainty of land redistribution resulted in many problems. Worried about the risk of losing their land and investment, farmers had no incentives to improve land conservation and agricultural infrastructure. They are likely to overexploit the soil to pursue short-term return and give priority to short-term crop production.

In summary, although China has a large territory, the arable agricultural land per capita is very limited. With the major economic development in recent years, the arable land is facing unprecedented pressures not only from the huge population but also from industrialization, urbanization and agricultural institutional reform. In addition, the quality of arable land is further shrinking due to land degradation. Arable land in China, as in some other countries, is suffering land degradation resulting from soil erosion, desertification, salinization and compaction. Soil erosion is the main cause of land degradation in Yunnan Province, where this research was conducted.

1.2 Land degradation and soil erosion

Soil degradation is the key sector of land degradation and the two are interchangeable in most cases. According to UNEP's GEO 2000 Report, it appears likely up to 1,900 million hectares of cropland and other land is affected by land degradation, including

550 million ha in Asia. Some 5-6 million ha of cropland is taken out of production annually because of severe soil degradation (UNEP/Earthscan, 1999). According to Oldeman *et al.* (1990), soil degradation globally reached 1965 $\times 10^4$ km^2, of which 110 $\times 10^4$ km^2 occurred in Asia. Soil degradation caused by soil erosion accounted for 84% of the total area of soil degradation (Oldeman, 1994). World losses of productive cropland due to soil erosion and associated degradation are estimated at ~60-70 $\times 10^6$ ha/year (FAO, 1989).

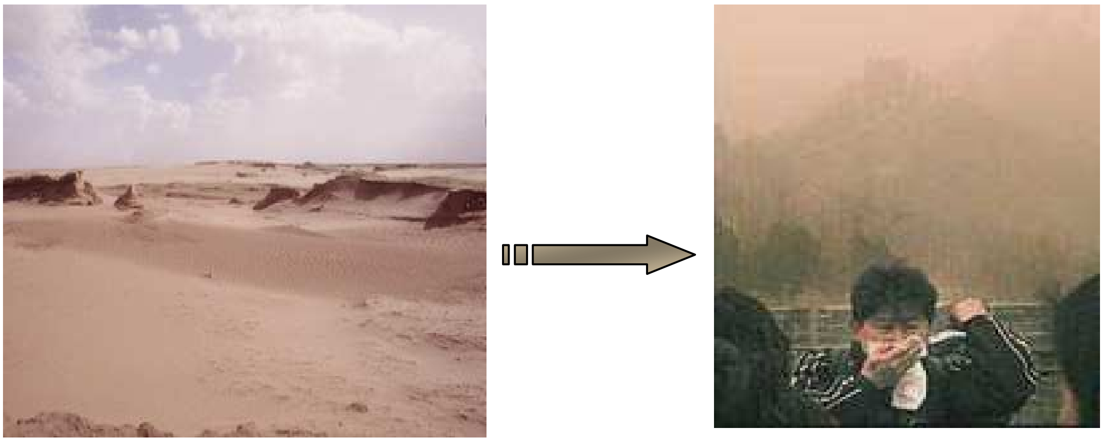
Soil erosion reduces soil productivity and sustainability, leading to land degradation, of which two-thirds is caused by washing away topsoil and the other third is wind erosion. GLASOD (Global Assessment of Soil Degradation) confirmed that soil erosion is the most important driving force for soil degradation. Water and wind erosion contribute 56% and 28% of the soil degradation, respectively. Deforestation, overgrazing and inappropriate agricultural management contribute 43, 29 and 24% of water erosion. The driving forces for wind erosion are 60% from overgrazing, 16% from inappropriate agricultural management, 16% from overexploiting natural vegetation and 8% from destroying forest (Zhang *et al.*, 1999). A 1991 land degradation study estimated that topsoil was being lost 16-300 times faster than it can be replaced through pedogenesis (Zhang *et al.*, 1999). Sabolics (1990) estimated the nutrient losses through runoff were almost the same as fertilizer production each year. A 1994 study estimated that soil degradation between 1945-1990 reduced world food production by 17%, including by 8% in Africa and as much as 20% in some Asian and Middle eastern countries (Topfer, 1999). The 50% of soil productivity decrease resulted from soil erosion and desertification. Some 75,000 million tonnes of soil were lost each year and caused $400,000 million damage (Eswaran *et al.*, 1999).

Now, soil erosion control is necessary in almost every country of the world under virtually every type of land use in both temperate and tropical climates (Morgan, 1995). Various additional soil-land degradation databases are available at local, regional and global scales, such as those found in Oldman *et al.* (1990); Dregne and Chou (1992); World Resources Institute (1992); and USDA (1994).

1.2.1 Land degradation brought about by wind erosion (desertification):

Desertification seriously deteriorates agricultural land. Desertification causes $6,500 m damage in China each year. Since the 1950s, expanding deserts have taken a toll of nearly 0.7 million ha of cultivated land, 2.35 million ha of rangeland and 6.4 million ha of forests, woodlands and shrublands. At present, as many as 2.6 million km^2 of land in China is desertified; each year an estimated 3,000 km^2 of land turns into deserts, compared to an annual expansion rate of 1,560 km^2 in the 1970s, 2,100 km^2 in the 1980s and 2400 km^2 in the 1990s (Lu and Yang, 2001). Mitchell *et al.* (1998) summarized 1.52 million km^2 of land are desert and desertified in China, which accounts for 16% of its total land area. The strong winds of late winter and early spring can remove literally millions of tonnes of topsoil in a single day. This soil can take centuries to replace and cause dust storms in Beijing, Tianjin and further in Korea and Japan (Plate 1.1).

Plate 1.1 Desert in Inner Mongolian and resultant dust storm in Beijing



1.2.2 Land degradation brought about by water erosion (soil erosion):

Land degradation constrains China's agriculture, economic development and ecological conservation. Beside the significant land desertification in north and northern west China, soil erosion is a major cause for land degradation all over the country, especially the middle-upper Yangtze River and Yellow River. Erosion by water removes topsoil and nutrients, reduces available water holding capacity and soil structural stability, causes surface sealing and reduces soil infiltration rates (Rhoton and Tyler, 1990). Pedological research showed that most of the A and A+B horizons were removed by soil erosion in southern China and the soil tended to be rocky (Li, 1988). The runoff removed soil nutrients and made soil deficient in some micro-nutrients in the Middle-Upper Yellow River basin (Yu, 1983). Studies on granite soils found that runoff removed surface clay, increased sand content, deteriorated soil structure and truncated soil (Wan and Shi, 1991). Loss of 1 mm of surface soil can decrease crop yields ~10 kg/ha, decrease soil organic matter by 50% and decrease maize yields by ~25% (Shi, 1991). One study showed that 8-80% of N and 7-30% of P was lost with eroded soil (Hubbard, 1983). Results from red soil are shown in Table 1.3.

Table 1.3. Mean nutrient content in topsoil (0-20 cm) of red soil, eroded at different severities in China

Erosion severity	Organic matter (%)	Total N (%)	Total P (%)	Total K (%)	Available N (mg/kg)	Available P_2O_5 (mg/kg)	Available K_2O (mg/kg)
Non	5.2	0.23	0.10	1.91	210.8	Trace	106.7
Slight	2.2	0.09	0.08	1.91	77.0	0.6	91.3
Medium	1.2	0.06	0.04	2.43	47.5	2.0	61.8
Severe	0.7	0.03	0.05	3.41	32.1	0.7	62.0

(Source: Zhang *et al.,* 1999).

1.2.2.1 Soil erosion in China: China's soil erosion problems are amongst the most severe in the world. Land resource pressures exerted by China's population are superimposed upon diverse environments, which are often geologically and geomorphologically unstable. Therefore, physical factors, such as slope steepness and stability, tectonic activity, rainfall erosivity and soil erodibility, interact with anthropogenic activities, producing a complex erosion problem. Thus, erosion is produced by a complex interplay of environmental and anthropogenic factors. It is estimated that 15-20% of the world's water erosion occurs in China (Brown, 1984; Wen, 1993). Soil degradation has been extensive and the eroded area in China is 3.67 million km^2, some 38.2% of the total area (Zhang and Lu, 1993; Wang and Wang, 2000). Water erosion is estimated to cause the loss of 5500 million tonnes (Mt) of soil per year, with associated loss of 27.5 Mt of organic matter, 5.5 Mt of Nitrogen, 0.5 Mt of available Potassium and 0.06 Mt of available Phosphorus (Wen, 1993). These losses account for 46, 2 and 63%, respectively, of the total N, P and K applied annually to croplands in China (Fullen *et al.,* 1997). The tillage erosion soil loss is estimated at 3.3×10^9 t/year and resultant food loss is estimated at 18-30 $\times$ 10^9 kg (Xue and Mermoud, 1995; Chen, 1989).

1.2.2.2 Soil erosion in Yunnan Province: This study was conducted in a typical catchment in Yunnan Province. Yunnan Province is a mountainous and hilly area located on the upper Yangtze River, where ~10% of land (38,209 km^2) is categorized as severely eroded (Chen, 1990). Intense convectional storms, embedded within the general southerly summer monsoonal airflow during the cropping season, makes erosion problems more pronounced (Plate 1.2). The practice of cultivating steep slopes is the norm throughout the Province. Most people in Yunnan depend very heavily on arable cropping agriculture. This has led to deforestation, cultivation of steep erodible slopes, overcultivation and adoption of unsustainable farming practices. People have no alternative but to cultivate slopes, as flat land is increasingly used for construction and population growth continues. Although there is a history of terracing in Yunnan, many areas were not terraced, as the expense and labour involved could not be justified for low value crops, such as maize. By the 1940s, 50% of the Province's forests had been removed. Between 1950-1977, forest cover throughout China declined dramatically and Yunnan was no exception, with cover dropping from 50 to 25% (Whitmore *et al.*, 1994). Some 3.55 million hectares of land were affected by soil erosion in mid-late 1980s in Yunnan, which accounts for 9.3% of the Province (Yang and Shi, 1994). The total eroded area now reaches 1.41×10^5 km^2 and occupies 36.88% of the total area in the 1990s (Bureau of Yunnan Hydrology, 2000). Chen (1990) reported that the eroded area was 1.47×10^5 km^2 in 1987 compared with 0.27×10^5 km^2 in 1980. Among these areas, 0.47×10^5 km^2 are located in the upper reaches of the Yangtze River, which accounts for 31.95% of the total eroded area in the Province.

Plate 1.2. Serious soil erosion during a single storm in Yunnan

Shi (1987) stated that ~ 0.3-0.5 cm of topsoil are lost annually in Yunnan and soil organic matter, nitrogen and phosphorus contents in eroded areas of Yunnan have decreased to 10, 5, and 2% of their original values, respectively (Shi, 1985). Whitmore *et al*. (1994) warned that accelerated soil and nutrient losses from Yunnan catchments might destabilize agricultural productivity and the agrarian economy over large areas in China.

Wen (1993) identified four soil erosion regions in China. Yunnan Province is in the southern erosion region. Soil erosion in southern China has become more critical in recent years. Over one-third of arable land has been adversely affected by soil erosion. Soil physical and chemical properties, coupled with the region's rainfall characteristics and abundance of steep land, indicate an environment where sustainable use of soils requires careful management. In the highlands of South China, family income of most farmers depends on crop production. These slopes are typically fragile, with high potential for soil erosion. Under the prevailing farming systems, however, the returns on these lands were often too low to induce farmers to invest in conservation measures. Consequently, inappropriate cultivation techniques severely degraded large areas of the red soils. Crop yields on some of the sloping land in South China have decreased by 30-60% because of soil erosion and in 50-100 years most topsoil will have been removed if the same cultivation techniques are used (Zhang *et al.,* 1999). Soil erosion causes loss and deterioration of soil, nutrients and damages soil structure, leading to non-sustainable production systems in the long term. The strategy to develop China's western region has been proposed. Decisions on reforesting and regrassing some of the dry sloping cultivated land, supported by GIS and Remote Sensing (RS) in Yunnan Province, has been conducted (Yang *et al.,* 2001). The Government also introduced a policy that prohibited cultivation of slopes >25°. However, this policy is not enforced, as enforcement would result in food shortages in the Province, due to a lack of suitable land <25° (Ni, 1993). Without integrated land use planning, a dramatic loss of crop productivity, biodiversity and increased environment problems can be expected.

1.2.2.3 Problems associated with the Three Gorges Dam: Several Chinese rivers are near the top of the world league table of sediment discharges. The Yellow River lies second, The Yangtze River fourth and The Pearl River sixteenth. The export of sediment from Chinese rivers to the oceans amounts to ~2000 million tonnes annually (Meade, 1996). Not all eroded soil reaches the sea. The dramatic shrinkage of natural lakes in recent years provides further evidence for the scale of contemporary sediment transfer (Table 1.4). Dong Ting Lake, linked to the lower course of the Yangtze River in Hunnan, experienced a 37% reduction in surface area and 40% shrinkage in capacity in the three decades up to 1977. Current sedimentation rates in the lake are 3.5 cm per year. More rapid sedimentation can be expected after the more extensive cultivation. In 1998, China was hit by the worst flooding for the century along the Yangtze River. Soil erosion was a key factor contributing to the devastating floods, which were exacerbated by deforestation (Li, 1999).

Table 1.4 The sediments of five freshwater lakes in the Lower Yangtze River

Lake	Sediments input (m.t/year)	Sediments output (m.t/year)	The net sediments (m.t/year)
Dong Ting	206	54	152
Bo Yang	22.8	11.6	11.2
Hong Ze	17.5	10.3	7.2
Cao	1.12	0.44	0.68
Tai	0.44	0.1	0.34
Total	247.86	76.44	171.42

(Source: Liu, 2001)

The Three Gorges Dam is also located in the middle Yangtze River, Hubei Province. The Yangtze River rises in the western uplands of the Qinghai-Tibet Plateau. Its 6300 kilometres length traverses a more humid landscape, through southern China. Much of Yunnan Province is located in the upper reach of this river. The headwaters are in tectonically active and geologically unstable uplands. Furthermore, the basin is generally under intensive agricultural use, mainly for rice cultivation. Hence, the erosion rates are high, estimated at 2400 million tonnes per year (Wen, 1993). These high rates are of increasing concern, especially considering the construction of the Three Gorges Dam in the middle section (Douglas *et al.*, 1994). Sedimentation within the reservoir could impair its efficiency and therefore soil conservation must be an integral component of basin management (Edmonds, 1994). Rapid reduction of storage capacity has compromized the objectives of many previous large dam schemes, including the Sanmen Gorge Dam built on Yellow River in 1961. The Chinese Government is now urging people to invest in erosion control in the Upper Yangtze Valley (Edmonds, 2000).

Over the last decade a widely stated objective in land resources management has been the adoption of strategies to ensure the sustainable use of land. Such an objective has been central to soil erosion conservation. The Chinese Government is greatly concerned with water and soil conservation. In 1991, the National People's Congress (NPC) promulgated the "Law on Water and Soil Conservation in the People's Republic of China". In 1993, soil and water conservation was declared a fundamental national policy to be continuously pursued. In the same year, the National Programme of Water and soil Conservation came into force. In 1994, China's Agenda 21 was formulated, in which measures on soil losses and desertification protection, as important components of a sustainable development strategy, were planned and arranged. In 1998, the Government of China signed the 'UN convention to Combat Desertification".

In summary, soil erosion is a pronounced problem in Yunnan Province. In order to strengthen the Province as a "green economic province", soil erosion control with maintaining or improving productivity ranks among the top concerns of the local government. Thus, sustainable land management is urgently demanded. New and innovative measures need to be developed and evaluated in accordance with local conditions.

1.3 Sustainable Land Management

1.3.1 Concept of sustainable land management:

Sustainable development means different things to different people. Many definitions have been proposed to describe 'sustainable development'. Their variety reflects the complexity of relationships involved. Environmental characteristics, market forces, social ambitions, development objectives and conservation aims are the forces and factors that interact to determine sustainable development. The FAO (1989) defined sustainable development as *"the management and conservation of the natural resources base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development in agriculture, forestry and fisheries sectors conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable."* Land as the main natural resource plays a key role in human life. Most sustainable developments are central to land sustainable management. Based on the above concept, the FESLM (Framework for Evaluating Sustainable Land Management) working group (1991) defined the sustainable land management as: *"it combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously: maintain or enhance production/services* *(productivity), reduce the level of production risk (security), protect the potential of natural resources and prevent degradation of soil and water quality (protection), be economically viable (viability), and socially acceptable (acceptability)*" (Smyth and Dumanski, 1993). Thus, sustainable land use has a much wider scope than sustainable agriculture. Thus, multidisciplinary research, led by users' needs, is therefore required (Latham and Syers, 1994)

In China, and many other countries, there is clear evidence of impending land shortages. Land resources suited to agriculture are already in use. Sustainable use and management of these lands is becoming a matter of life or death for the increasing population and future generations. Past emphasis on land production is forced to give way to balance the finite extent of fertile land and the seemingly insatiable demands of growing human populations. So far human ingenuity has managed to strike the balance on a global scale—if often not the regional or local scale. But the methods used have not yet been sustainable as described in Section 1.2.

Since FAO posted the problem of land degradation in 1971, UN hosted a conference on land desertification at Nairobi in 1977. UNEP funded the GLASOD (Global Assessment of Soil Degradation) Programme in 1990 (Oldeman, 1991 and 1994) and 1992 (Dregne and Chou, 1992). The first and second international conferences on land degradation were held in 1996 and 1999, respectively. In Asia, the network of ASOCON (Asia Soil Conservation Network funded by FAO and UNDP), ASIALAND, IBSRAM (International Board for Soil Research and Management) and ASSOD (Assessment of Soil Degradation Induced by Human Activities in Asia) have done much work on the assessment and control of soil degradation. Meanwhile, many national and regional projects were funded to assess and control land degradation. In China, research on land degradation has been mainly funded since the 1990s. Much work still needs to be done, especially at regional and local levels. Since the diversity of environmental factors present considerable variations from one place to another, there is no universal recipe for sustainable land use.

1.3.2 Sustainable land management central to soil conservation

Considerable efforts have been made and experiences and lessons gained from attempting to develop more sustainable land management worldwide. There is an urgent need to make better use of existing solutions and technologies. Sustainable land management is dynamic and site-specific. Studies need to be carried out to evaluate the existing solutions and identify the best practices for specific sites at different scales. In Yunnan Province, sustainable land management is central to soil conservation. The useful research solutions advocated by Morgan (1995) and El-Swaify *et al.* (1982) are summarized in Figure 1.2.

In Figure 1.2, agromonic or biological measures for soil erosion use the protective effect of plant cover to reduce erosion. The above-ground components, such as leaves and stems, absorb some of the energy of falling raindrops, running water and wind, so that less is directed at the soil, whilst the below-ground components, comprizing the root system, contribute to soil mechanical strength. Mulching, multicropping and agroforestry are very popular measures used in this category. The main aim of sound soil management is to maintain fertility. Highly fertile soils have a stable structure and a high infiltration capacity, result in good plant cover and thus minimize soil erodibility. The conservation tillage and organic matter and soil conditioner applications to promote good soil structure and suitable conditions for plant growth are favourable when establishing soil conservation strategies. Mechanical field practices are used to control the movement of water and wind over the soil surface, normally in conjunction with agronomic measures. Terracing and contouring are widely employed.

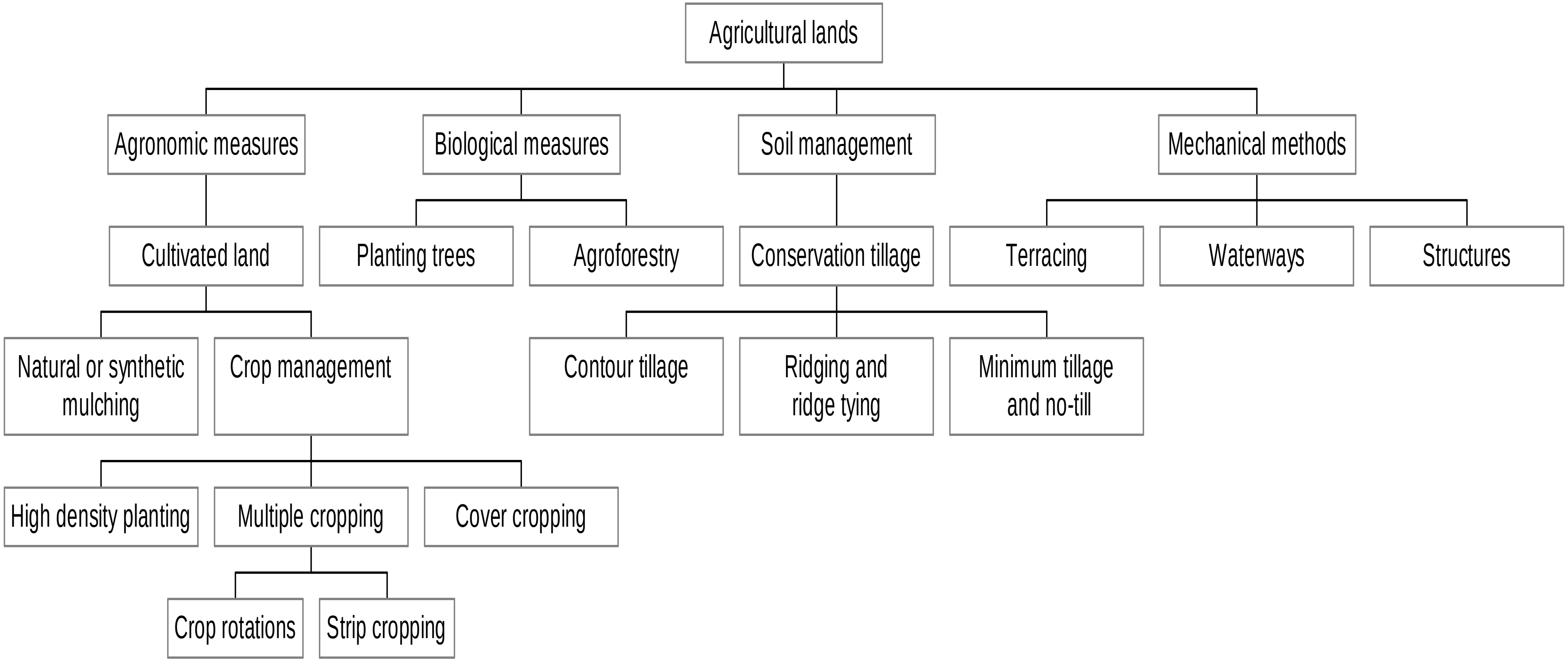
Contour cropping

Carrying out ploughing, planting and cultivation on the contour can reduce soil loss from sloping land compared with cultivation up-and-down the slope. The effectiveness of contour farming varies with slope length and steepness. The allowable interval length declines with increasing steepness and effectiveness is improved by supplementing contour farming with strip cropping (Morgan, 1995).

Contour planting is a simple yet effective conservation practice and easily accepted by farmers. Neal (1963) found reductions of ≤50% in soil loss due to contour planting on slopes of 4-6°. Fullen *et al.* (1996) found contour planting reduced soil loss in Yunnan Province, while Milne (2001) reported that seasonal soil loss was significantly reduced by ridged contour planting on slopes of 3°and 10° in 1998. Similar results were obtained by Barton in 1995 and 1996 (Barton, 2000).

Contour ridges can increase storage capacity and reduce erosion. It reduced soil loss to 9.9 t/ha compared with 15 t/ha without ridges under cabbage and cauliflower on trial plots over two years in Venezuela (Rodriguez and Fernandez, 1992). Ridge cultivation

Figure 1.2 Strategies for erosion control on agricultural land



(Source: compiled from El-Swaify *et al.*, 1982; Morgan, 1995) of cassava on 3° slopes reduced soil loss to 16.8 t/ha compared with 29.5 t/ha for flat bed cultivation and 22.2 t/ha for mound cultivation (Odemerho and Avwunudiogba 1993). Contour ridge cultivation reduced soil loss to 6.49 t/ha compared with 19.64 t/ha of up-and-down ridge cultivation on purple soil in Sichuan Province (Zhang *et al.*, 1999). Field experiments in Yunnan Province (Liu and Wu, 1991) and Shanxi Province (Wang and Yue, 2000) also showed that contour ridge cultivation can reduce soil erosion and increase maize yield compared with the up-down slope cultivation.

Tied ridges (connecting the ridges with cross-ties over the intervening furrows, thereby forming a series of rectangular depressions which fill with water during rain) can further increase water storage and be effective for erosion control (Plate 1.3). Tied ridging with minimum till gave soil loss of <0.5 t/ha compared with 9.5 t/ha for conventional ploughing over three years (Vogel, 1992). Experiments on wheat in Israel showed more yield and less soil loss with tied ridges over winter 1980-1981 (Morin *et al.*, 1984). Tied ridge cultivation reduced soil loss to 1.91 t/ha compared with 19.64 t/ha of up-and-down more ridge cultivation on purple soil in Sichuan Province (Zhang *et al.*, 1999). Tied ridges increased yields of millet, maize and cotton in average and dry years, but not in wet years in Sudan (Hulugalle, 1988). This practice should only be used on well-drained soils to avoid water logging. Additional measures, such as contour bunding and terracing, contour strip-cropping and grassing, contour alley cropping and contour hedgerows can also be employed, often with considerable soil conservation effects.

Plate 1.3 Tied ridges for erosion control on purple soil in Sichuan Province

Mulching

Mulching is the covering of the soil with synthetic materials (such as plastic film) and natural materials (such as crop residues). A mulch simulates the effect of a plant cover to reduce soil loss. It also adjusts soil temperature and soil moisture and thus can affect crop yield.

Straw mulch used to be a common practice in some regions of China. Zhu *et al.* (2000) found straw mulch with contour tillage further reduced soil loss to 5.7 t/ha compared with 25.6 t/ha of contour ridge tillage on a 13.5° slope. In the Netherlands, compared with conventional systems, straw mulch reduced runoff and soil loss by 46.5% and 89.5%, respectively (Kwaad *et al.,* 1998). Straw mulch also conserved soil water, improved soil water availability and thus increased crop yield, especially in areas with limited rainfall (Wu, 1990; Li *et al.,* 1994; Fullen *et al.,* 1999a; Wang, 2003). The results from red hilly areas in southeast China are shown in Table 1.5. Straw mulch also adjusts soil temperature (Berry *et al.,* 1987) and increases soil fertility (Karlen *et al.,* 1994). Nowadays in some regions of China, the rice and wheat straw is collected and burnt for disposal. This practice is causing air pollution and is unsustainable. Steps to promote farmers using straw as soil cover on sloping land during rainy season are required.

Table 1.5. Effect of straw return on soil fertility

Treatment	Organic matter (g/kg)	Total N (g/kg)	Total P_2O_5 (g/kg)	Total K_2O (g/kg)	Available P_2O_5 (mg/kg)	Available K_2O (mg/kg)	pH
High straw rate	13.36	0.82	0.82	91.0	41.0	132.9	4.85
Low straw rate	12.67	0.76	0.68	88.2	28.0	133.5	4.88
No straw return	11.63	0.70	0.69	84.0	37.5	135.2	4.76

(Source: Zhang *et al.*, 1999)

Polythene mulch has been proved to retain soil moisture, increase soil temperature and thus increase crop yield (Lei *et al.,* 1994; Zhang *et al.,* 2000). Sun (1990) found the highest yield from polythene mulch. The yield of maize with polythene mulch increased 20.4-23.1% compared with no-mulched treatment (Xie, 2001). As a common practice for many crops in China, the benefit of increasing yield was widely reported. However, Fullen *et al.* (1999a) and Panomtaranichagul *et al.* (2001) found adverse effects on erosion rate in downslope plots. The impermeable plastic mulch prevented infiltration and caused higher erosion rates, particularly on steep slopes and when up-down cultivation was employed. So polythene mulch is inappropriate for steep slopes in terms of soil conservation. Furthermore, continuous use of plastic film has negative environmental effects, known as ‘white pollution’. Studies show that ~37.5 kg/ha of plastic remain in the soil on average when the land has been covered for >3 years. If the remaining plastic pieces weighed 45.0 kg/ha, the vegetable yield would decrease by 2-10% compared with the farm land without plastic coverage (Li *et al.*, 1997), this may be related to root development and soil water movement. Several mulches of other materials exist, such as maize stalks, wood chips, palm fronds, standing stubble, compost, hay and decomposed paper.

Intercropping

Intercropping (growing two or more crops on the same piece of land at the same time) increases production, whilst providing protection from soil erosion. It has been traditionally practised in China. Liu and Wu (1991) found intercropping maize with potato reduced runoff, soil losses, organic matter loss and nutrient loss by 22.2, 56.4, 50.8 and 51.4%, respectively. Intercropping maize with cassava offers the advantages of a two-storey canopy, giving a higher interception capacity and reducing soil particle detachment by raindrop impact to 35-60% of the respective values from cassava or maize alone in the tropics (Lal, 1987). Intercropping maize with leguminous ground covers is more effective. Soil loss reduced to 2.0 and 2.4 t/ha, respectively, when maize was intercroped with rose clover (*Trifolium hortum*) and kalo (*Lotus corniculatis*), compared with 4 t/ha from maize alone during the 135-day cropping season (El-Swaify *et al.*, 1988). The annual grain legume-based cropping systems were 32-49% more profitable than continuous sole maize, making them attractive to small farmers in semi-arid tropics (Rao, 2000). Furthermore, legumes provided 90-125 N kg/ha to the following crop by nitrogen fixation (Bruulsema and Christie, 1987). Legumes were used as green manure crops to maintain soil fertility and increase agricultural productivity in ancient China (Gong *et al.*, 2003). Fu and Chen (2000) recommended intercropping using different crops, grass and fruit trees to increase biodiversity and create a more patchy landscape. Zhu *et al.* (2000, 2003) found that rice blast incidence was significantly reduced when intercropping high yielding hybrid varieties with old glutinous varieties in Yunnan Province.

Agroforestry

Where trees are deliberately integrated with crops or animals or both to exploit expected positive interactions between the trees and other land uses, the practice is defined as agroforestry (Lundgren and Nair, 1985). Agroforestry is encouraged in many countries as a way of modifying existing farming systems to promote soil fertility, erosion control and a diversified source of income. Multi-purpose trees and shrubs are promising in agroforestry. Trees or bushes can be planted contour-aligned as contour hedgerows in intercropping. This technique can reduce surface runoff and soil loss by 50-70% and 97-99%, respectively, and increase organic matter and crop yield by 25-35% and 30-60%, respectively (Tang *et al.*, 2001). Hedgerows with grass strips or natural vegetation were more attractive to farmers due to their low establishment and maintenance cost in The Philippines (Nelson and Cramb, 1998). In Northern Thailand, vetiver grass strips and alley cropping are important conservation practices. Alley cropping with Mango-hedgerow tree and Graham Stylo surface cover was the most effective treatment for decreasing runoff and soil loss and had the most uniform soil fertility and crop development along the slope (Panomtaranichagul *et al.*, 2001).

Afforestation

Afforestation programmes have been implemented in many countries to arrest erosion and regulate floods. Bamboo, teak, sissoo and eucalyptus were successfully planted as the most promising species in India (Tejwani, 1981). The principal species in forest plantations in Kenya are *Cupressus lusitanica*, *Pinus patula*, *Pinus radiata* and *Eucalyptua saligna* (Konuche, 1983). *Pinus yunnanensis* and *Pinus armandii* Franch are satisfactory in Yunnan. Results from The Leaping Tiger Gorge on The Upper Yangtze Basin in Yunnan showed that the pine (*Pinus yunnanensis* Franch) forest can play a significant role in slope protection, to the extent that soil loss in the forest is 50% less than on non-vegetated land (Watts, 2000).

The above selected practices, contour cropping, mulching and intercropping, for soil conservation were suggested and evaluated in farmers' plots in Wang Jia Catchment as part of this research work. Agroforestry and afforetation was also implemented in the catchment as part of land use change.

1.4 Land Use Evaluation:

1.4.1 Land use related to soil erosion:

Since 1986, major advances have been made in the study of erosion. However, the resolution of soil erosion will not be achieved by technical solutions alone. Proper land use plays a key role in erosion control. Land use may influence many natural phenomena and ecological processes, including soil erosion and nutrients. Analysis of the relationship between soil erosion and land use based on GIS suggested that there is a close relationship (Zou *et al.*, 2002). Soil erosion rates vary significantly in different land uses (Chen, 2002). The cultivated sloping land, bare sloping land and natural grassland with low vegetative cover have the highest erosion rate in Qingbiankohe Catchment (Tang *et al.,* 2001). A close spatial correlation between abandoned cultivated land and severe gullies is identified in South Africa by Kakembo and Rowntree (2003). Soil erosion related land use type and management practices is the most important reason for soil degradation in Hunan Province, China (Shi *et al*., 2001). It was also reported that 33.7% of total agricultural land in Thailand are degraded due to improper utilization of marginal land and poor management practices (Dent, 1989). Soil fertility evaluation on red soil (Ultisol) hills of Hubei Province at township level shows that soil fertility was closely related to land use types (Cai *et al.,* 2000). Characterizing soil nutrients in relation to land use types is important for assessing the effects of future land use (Wang *et al.,* 2001). Poor land use planning, a dramatic loss of crop productivity, decreased biodiversity and increased environmental problems can be expected. Unsuitable land uses are popular phenomena, especially for agricultural production, because soil fertility and environmental concerns rank low among farmers' priorities in some regions in China. The improved economy of individual households might be of short duration if farmers cannot be sensitized to new and sustainable resource management options. However, the best land use type must cope with the local physical, economic and social setting and have to be developed in line with farmers' priorities and the fragile environment.

1.4.2 Land suitability assessment:

1.4.2.1 Concepts:

The function of land use planning is to guide decisions on land use in such a way that environmental resources are put to the most beneficial use, whilst at the same time conserving those resources for the future. This planning must be based on understanding both the natural environment and the land use envisaged. There have been many examples of damage to natural resources and of unsuccessful land use enterprises through failure to take account of the mutual relationship between land and the uses to which it is put. It is a function of land evaluation to bring about such understanding and to present planners with comparisons of the most promising land uses.

Land evaluation is a process to match land characteristics with land use requirements, which is designed to serve practical purposes, to contribute to the best use of land resources. The decision of appropriate land use is made based on land use evaluation, which requires vast information, to build an evaluation index and process the evaluation which will take into account many aspects, such as environmental, economic and social factors. When used for specified purposes, land use involves the execution and interpretation of basic surveys of climate, soils, vegetation and other aspects of land in terms of the requirements of alternative land uses. Thus a multidisciplinary approach is required. To be of value in planning, the range of land uses considered has to be limited to those which are relevant within the physical, economic and social context of the area considered and the comparison must incorporate economic considerations.

Where land suitability is evaluated without taking the social and economic aspects into consideration, the assessment should be the land physical suitability only. The land suitability assessment is the first part of land use evaluation and is based on the suitability of the land for kinds of land use. The fitness of soils for land use cannot be assessed in isolation from other aspects of the environment and hence it is land which is employed as the basis for suitability evaluation (FAO, 1976). Land characteristics, such as slope angle, rainfall, soil texture, available water capacity and vegetation biomass can be measured or estimated. However, land characteristics should not be employed in evaluation directly because of the interaction between characteristics. Land quality is a complex attribute of land which acts in a distinct manner in its influence on the suitability of land for a specified use. Where the data are available, aggregate land quality may also be employed, e.g. crop yields. Land qualities can sometimes be estimated or measured directly, but are frequently described by means of land characteristics. Qualities or characteristics employed to determine limits of land suitability classes or subclasses are known as diagnostic criteria. Selecting diagnostic criteria is essential to the accuracy of land evaluation results. Principal component analysis and analytic hierarchy processes were employed to determine the weight for each evaluating factor (Yin *et al.,* 1997; Wu, 2000).

Emphasis on “suitability” has arisen because of increasing worldwide concern about environmental degradation and various related processes, such as soil erosion, degradation and loss in genetic biodiversity, which are known to have adverse effects on agricultural productivity. Land is best conserved if utilization is based on its supporting capacity for cultivation. Hence, there is the need for agronomically-sensible and technically-appropriate solutions to improve land productivity and environmental conservation. It is on this premise that this study was carried out, to determine the potential of the land for maize cultivation, and assessing land quality with the purpose of both improving land quality and conserving the environment.

1.4.2.2 Approaches:

Direct land evaluation: Land may be evaluated directly, by experiments, that is by growing the crop for agricultural production evaluation, to assess results. The most direct method of land evaluation for agricultural purposes is the collection and processing of crop-yield data. Crop yield-data from a few sites can be used to derive mathematical models which relate yields to environmental factors. The results are applicable only to the specific trial sites and for that particular use. Direct evaluation is of limited value. Most land use systems are indirect.

Indirect land evaluation: the development of an indirect land evaluation system involves identification of the important soil and site properties which affect the success of a land use. The system is then constructed so that values of these properties either define categories (c*ategoric system*) or may be combined mathematically to give an index on a sliding scale (*parametric system*).

Categoric systems, or qualitative evaluation, groups land into a small number of discrete ranked categories according to the limiting values of a number of soil and site properties (limitation approach). These properties are believed to be those which impose permanent limitations on the range and success of suitable land uses. Land classes are defined according to the lowest class level of one or more characteristics (Sys *et al.*, 1991). Categoric systems are widely used in assessing land for irrigation, forestry and a wide range of non-agricultural uses (McRae and Burnham, 1981).

Parametric systems or quantitative evaluation combine various soil and site properties (parameters) that are believed to influence yield in mathematical formulae. Some parametric systems are simple, others are extremely complex. Systems differ in the factors they include and in their mathematical manipulation. Three main kinds of manipulation can be recognized:

Additive, e.g. $P = A+B+C$

Multiplicative, e.g. $P = A \times B \times C$

Functions, e.g. $P = A\, f(B \times C \times D)$

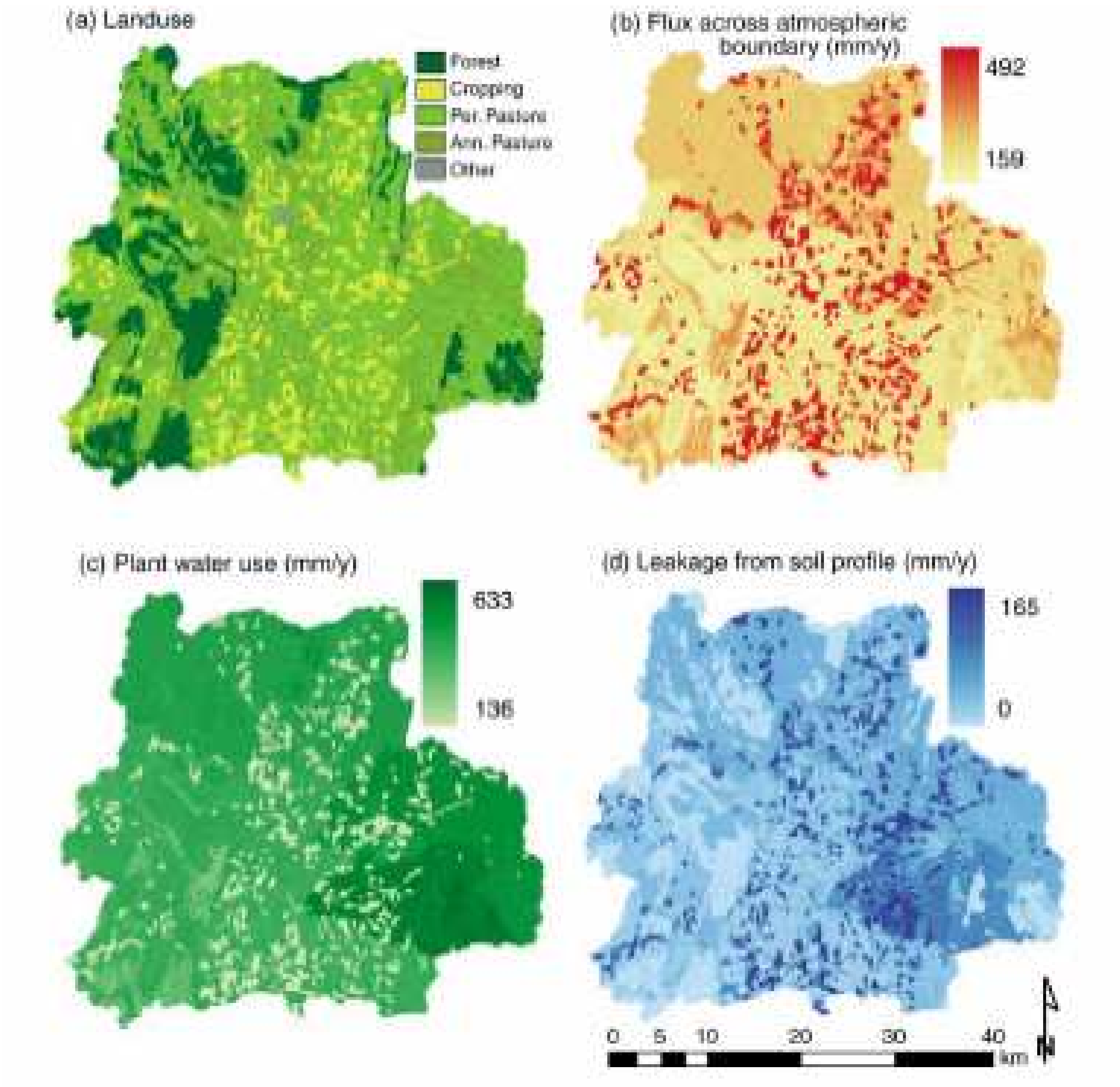
Where P is the parametric rating, score, or index, and A, B, C and D are soil and site properties (McRae and Burnham, 1981).

The mixed evaluation (quality and quantity) predominantly uses geographically referenced input data. Therefore, a linkage with geographical information systems (GIS) is a prerequisite for efficient use. After storage in a GIS, some recent projects showed that the mixed approach saved 50–70% of time compared with application of the quantitative evaluation method to all units (van Lanen *et al.,* 1992).

1.4.3 GIS as a tool

As described in the FAO Framework for Land Evaluation (FAO, 1976), a multidisciplinary approach is required. The collection and processing of a large quantity of good quality and reliable information that allows timely and proper decisions are required. GIS has proven to be a useful tool in this field (Tulloch *et al.,* 2003). Result maps produced with GIS is inherently visual (Figure 1.3). The way to deal with such information used to be very complex and labour- and time-consuming. However, adequate Geographic Information Systems with databases, allowing comparatively simple and quick access to required information (both in the form of specialized maps and numerical and/or textual data) are needed (Bogunovic and Husnjak, 2000). The importance of application of GIS technology is proven by a high confidence of tools for analysis of complex ecological features and by possibilities of modelling and correlating ecological data with management. Analysis of information generated through the mapping and evaluation procedure necessitates procedures that can accommodate the spatial dimension. GIS has the ability to handle this type of information and possesses the requisite specialist analytical tools. Where considering alterations to the physical environment, GIS offers a range of options for dealing with uncertainties, through data handling, modelling and visualisation. The integration of GIS into planning and policy-making is the key to the success or failure of many applications (Worrall, 1989). Although decision-support approaches pre-date the use of GIS, explicitly using an evaluation and GIS operating procedure in tandem produces primary advantages (Villa *et al.*, 1996).

Figure 1.3. (a) Current landuse map of the Mandagery catchment, Australia. (b–d) mean annual fluxes (1975–95) for each landuse and soil type combinations.



(Source: Tuteja *et al.*, 2003)

Even if detailed evaluations are not possible, broad-based GIS techniques offer relatively cheap and effective methods for preliminary survey of land-use change options (Schaller, 1992; Aspinall, 1994). This is particularly the case in linear developments, where a site-by-site survey is inadequate, since it "fails to take account of wider effects on habitats and species due to progressive habitat loss and fragmentation" (Treweek and Veitch, 1996). On the basis of investigations into soil erosion factors, synthesizing land types, soil type, elevation, slope and the minimum distance by means of GIS was established for soil erosion prediction (Gobin *et al.*, 2004). Differences exist in spatial and temporal distribution of soil erosion in dealing and analyzing these features in modelling, but GIS is a very powerful tool (Pan, 1997).

Land information systems (LIS) is an application of GIS, which can contain agricultural, soil, irrigation, demographic, climatic, meteorological and elevation information, in addition to the graphical sketches depicting land holding, ownership related information and village maps (de Vries, 2003). This system is a key to the country's sustainable development (Hallett *et al.,* 2003). A single and uniform national level LIS should be evolved for demands (Chandrasekhar, 1995). The land information system made it possible to incorporate several aspects of the US Food Security Act (1985) into the soil erosion control planning with little additional technical or economic investment (Ventura *et al.,* 1988). The principle of designing land information systems was discussed by Xiang Nanping (2001). GIS have given rise to revolutionary changes in conventional LIS. The implementation of GPS and GIS in LIS has numerous advantages, such as speedy and accurate data collection; economy and ease of implementation. Land information systems can be an alternative, which can provide more efficient systems for land management. A GIS-based LIS is a digital system having spatial and non-spatial data for each land holding. Since the two are maintained in digital form, it is possible to edit, rectify and keep the record up-to-date with minimal effort (Sharma, 2002). This merges the spatial and attribute information, and makes LIS more quantifiable, standardized and comprehensive (Wu *et al.,* 2001). Land use information systems based on GIS were established in Ningxia Province, Northwest China (Li and Li, 1996). The agro-ecological information system established in Qingshishan Catchment was used for land suitability assessment and catchment planning (Lu *et al.,* 2000). Creation of a GIS-based land resource information system (LRIS) of Doumen County shows that LRIS would provide land resource management models for the counties of the Pearl River Delta and prepare requisite work for the creation of land management systems in Guangdong Province (Huang *et al.,* 1999). A multilingual soil profile database is an essential part of land resources information systems (de la Rosa et al., *2002*).

Soil information systems (SIS). Soil information systems are an active research area advancing global soil science in recent years. There is an urgent demand in different industries for soil scientists to develop SIS in order to connect to the international Soil and Terrain Digital Database (SOTER) (Zhang *et al.*, 2001; Igue *et al.*, 2003). Huang *et al.* (2002) reported that GIS based databases contributed to the development of SIS in Fujian Province and all China. Studies of system structure, integrating soil and land databases and applying precision agriculture are current research areas of GIS in China. The general design and construction of the SIS in Guizhou Province were discussed and it is expected to play an important role in territorial planning, agricultural sustainable development and spatial assessment of the ecological environment (Zhou *et al.*, 2000). Data collection, updating, decoding and developing should receive more attention (Wei, 2002). The contents of a soil information system of Dafeng City, Jiangsu Province were introduced and the techniques for building the system, especially the techniques used for coding soil attributes and digitizing lines and polygons of concerned maps were discussed by Pan *et al.* (1999). Additional to the use for land evaluation, SIS can be used in many aspects. SIS was used to combat soil erosion and runoff from agricultural land in many countries. As more digital soil information becomes available, its use in making land use planning decisions based on GIS analyses will undoubtedly become increasingly common. The quality of those decisions will continue to depend on the quality of the geographic soil information provided by soil scientists and the quality of the decision criteria developed by planners and their clients.

Land evaluation is a comprehensive assessment of the biophysical properties of the land. As a multi-disciplinary approach, land evaluation involves the creation of a database composed of diverse and multi-criteria information. GIS can make the evaluation work more efficient and accurate (Yin *et al.*, 1997). Studies by merging model and soil information systems in Jianhan Plain-Lake District showed that GIS-based agricultural land suitability evaluation, as a prerequisite in determining rational land uses, is very important in land resource planning and management (Xie and Zhang, 1994). By integrating the numerical calculation with graphic processes, GIS makes land suitability evaluation more effective (Li and Wang, 2000). GIS-based AHP can be used to select key factors for a multi-objective land use appraisal (Wu, 2000). Rajendra and

Apisit (1995) assessed land suitability for major crops, such as maize, in the Muallek area of Thailand. Studies at county level showed that the land unit gives different suitability classes for different crops in China (Ouyang and Yu, 2002). Furthermore, evaluation at different scales may give different suitability classes for the same land unit (Verburg and Chen, 2000). Based on previous work in the field, this research develops a generic land information system suitable for subtropical highland catchments and for evaluating more sustainable cropping systems based on the cultivation of maize as the major arable crop on sloping lands.

1.4.4 Land requirements for maize production:

The tested catchment is in a main area of maize production, where farmers usually grow maize and tobacco in the uplands in summer and wheat and peas in winter. Tobacco production used to be the dominant crop, but has begun to decline. Maize production will play a major role in agricultural production. It is important to evaluate soil suitability in terms of maize production and to guide farmers with choices of different land uses. In the land unit where the maize planting is unsuitable, sweet chestnut, prickly ash tree or timber pine production was introduced according to site conditions, such as slope, altitude and soil moisture regime.

1.4.4.1 General:

Maize (*Zea mays* L. ssp. *Mays*) is a major cereal and cultivated worldwide for thousands of years. It is the third largest staple food now in the world by volume, after wheat and rice. The extreme adaptability of maize is reflected by the cultivation of modern cultivars in a variety of environments, from sea level to 3800 m asl and wet coasts to sand dunes (Nabhan, 1989). The physical conditions for maize growth are quite variety specific. Thus, when defining the land-use requirements in land evaluation, the maize cultivars to be cropped must be considered.

Maize is a C4 species and a member of the Gramineae grass family, with optimum photosynthesis at 20-30°C. Maize development stages include initial 15-30 days, development 30-45 days, mid season 30-45 days, late season 10-30 days, total cycle 100-140 days. Mean rooting depth is 1.0-1.7 m. Grain yields are normally at 10-13% moisture content and water utilization efficiency for harvested yield is 0.8-1.6 kg/m^3 (Sys *et al.*, 1991).

1.4.4.2 Soil and climate conditions for maize:

Climate, soil conditions and agricultural practices influence maize growth and yield. Although maize has good adaptability, its susceptibility to frost makes the number of growing days the most important limiting factor in its production. Some hybrid maize varieties require a growing season of ~120 frost-free days and if grown in dry conditions may require longer to mature (Minnis, 1985; Muenchrath and Salvador, 1995). Maize needs high light intensity during its whole life and shading after pollination can significantly reduce yield (Shun, 1997).

Maize can be planted where the accumulated ≧10°C temperature is >1900°C and average air temperature is >18°C in summer. Generally, 10°C was treated as biological zero degree for maize growth. Maize requires a minimum soil temperature of 12°C for germination. From emergence onwards, maize grows optimally at an average daily temperature of 24°C and night temperature of 14-16°C. Below 12°C maize shoots show little growth (Purseglow, 1972). Time for seed emergence depends on temperature. Emergence under 10-13°C, 16-18°C and >21°C needs 18-20, 8-10 and 5-6 days, respectively. If temperature is >40°C, seed germination is stopped. After seeding, maize grows well with temperatures of 25-35°C and the staminate flower growth advances by 5-7 days with temperature increasing by 1°C (Shun, 1997). Maize yield decreased by 7.6% when the accumulated temperature was reduced by 100°C. Different cultivars require different accumulated temperatures and these vary with sowing season (Table 1.6).

Table 1.6. Accumulated temperature (°C) requirements for different maize cultivars

Maturity of cultivar	Very early	Early	Medium	Late	Very late
Σ T ≧10°C (°C)	<2100	2100-2400	2400-2700	2700-3000	>3000

(Source: China Maize Production, 2003)

Adequate annual rainfall (600-1000 mm) is required for short-season maize production. Additional rainfall is required for high intensity production and where longer growing seasons exist. Purseglow (1972) and Muenchrath and Salvador (1995) found that modern hybrid maize requires ~400-600 mm of water during the growing season. Generally, 150 mm of growing season rainfall and 350 mm annual rainfall is considered the lower limit for maize production without irrigation. Inadequate rainfall during the early season can cause poor establishment and in extreme situations, crop failure. It has been reported that water deficiency when the maize is at the tasselling or silking stage may decrease yields by 50-75% (Classen and Shaw, 1970; Minnis, 1985; Muenchrath and Salvador, 1995). Shun (1997) estimated ~3000 m^3 water is required per hectare.

When soil thickness was <10 cm, the maximum plant height of maize was only 50 cm and plants failed to flower. In the fields with soil thickness of 10-30 cm, only 25% maize plants produced grain and estimated grain yield was just 60-99 kg/ha (Joseph *et al.*, 2001). Sys *et al.* (1991) summarized the soil fertility (nutrient content) for maize growth (Table 1.7). Slightly different data have been used as the soil requirements of maize for land evaluation in South-western Greece (Yialouris *et al.*, 1997).

Table 1.7 Nutrient availability requirements of maize

Fertility factors (0-15 cm)	Suitable levels			
	Good	Fair	Poor	Not
pH	5.5-7.0	7.0-8.2	>8.2	-
		5.2-5.5	<5.2	-
Organic matter(%)	>1.5	0.7-1.5	0.5-0.7	<0.5
CEC (me/100g)	>8	6-8	3-6	<3
Ca (me/100g)	>3.8	2.6-3.8	1.0-2.6	<1.0
Mg (me/100g)	>0.9	0.6-0.9	0.3-0.6	<0.3
K (me/100g)	>0.3	0.2-0.3	0.1-0.2	<0.1

(Source: Sys *et al.*, 1991)

1.4.4.3 Maize production in Yunnan Province

China is the second largest producer of maize, with 19 million hectares. There are six main planting regions of maize in China. Yunnan Province falls in the south-west mountain region. Maize has a good adoption to different growth conditions and is produced all over the Province. Rice used to be the first staple crop in terms of both total yield and area planted before 2000. Owing to agricultural structural reform, the planting area of maize has become the largest among the food crops since 2000. In 2001, maize production occupied 1.14 million hectares, which accounts for 28.96% of the total food production area. Total yield reached 4500 million kg with an average yield of 3952 kg/ha, which accounts for 33.25% of the total food crop yield. The unit yield increase was contributed by high fertilizer input, insecticide application, hybrid seed and advanced agricultural technology (Zhou, 2002). Tobacco production used to be a mainstay industry and has began to decline. The increase of maize production and productivity is shown in Table 1.8.

Table1.8. Maize production in Yunnan Province

Year	Area sown ($\times 10^3$ ha)	Total yield ($\times 10^4$ t)	Unit yield (kg/ha)
1979	1059.7	225.0	2123
1985	920.3	248.7	2700
1990	989.9	280.6	2835
1995	988.5	339.5	3434
1998	1095.7	418.1	3815
1999	1159.6	459.5	3963
2000	1138.1	473.3	4194

(Source: China Maize Production, 2003).

Maize is sown in mid-late May and early June and harvested in mid September to early October in Yunnan. It can also be sown in summer, autumn and winter according to different regions. Maize grows over a wide altitude, from Honghe Valley at 76.4 m asl to some high mountain areas at 3200 m asl. Although maize is mainly used for fodder, it is still a staple food for people residing in the mountains. Improving maize production in a sustainable way is crucial for increasing their income and releasing poverty in rural area.

1.5 Soil quality and fertility evaluation

1.5.1 Concept:

The concept of soil quality has been in use since the 1950s, especially by pedologists who developed methodology and criteria for land evaluation and soil capacity assessment. The use of the specific term “soil quality” since the late 1980s is related to the issues of sustainability, particularly with regard to agricultural sustainability. Since the late 1980s, soil scientists have denoted the soil’s capacity to perform specific functions by the term “ soil quality” (Lal, 1993; Larson and Pierce, 1991; Papendick and Parr, 1992; Pierce and Larson, 1993; SSSA, 1987). Johnson *et al.* (1997) proposed that “ *soil quality is a measure of the condition of the soil relative to the requirements of one* *or more species and/or to any human needs or purposes*". Doran and Parkin (1994) defined soil quality as *"the capacity of the soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health"*. This definition is similar to those proposed by Acton and Gregorich (1995), Karlen *et al.* (1997) and Larson and Pierce (1991). Soil functions are: *(1) sustaining biological activity, diversity, and productivity; (2) regulating and partitioning water and solute flow; (3) filtering and buffering, degrading, immobilizing, and detoxifying organic and inorganic materials, including industrial and municipal by-products and atmospheric deposition; (4) storing and cycling nutrients and other elements within the earth's biosphere, and (5) providing support of socioeconomic structures and protection for archaeological treasures associated with human habitation* (Seybold *et al.*, 1998).

The broad concept of soil fertility means the integrated and rational conditions of soil related to soil moisture, porosity, temperature and nutrient content. Soil fertility was defined as the integrated status of soil nutrient content and the environmental conditions associated with the soil providing crop nutrients. More precisely, soil fertility is referred to as soil nutrient content. Foth and Ellis (1988) defined soil fertility as *"the status of a soil with respect to its ability to supply elements essential for plant growth without a toxic concentration of any element"*. Thus, soil fertility focuses on an adequate and balanced supply of elements or nutrients to satisfy the needs of plants. Because plants have different needs for the essential elements and different tolerances of the toxic elements, a soil can be fertile for one plant and at the same time be infertile for another. In this study, soil fertility is mostly associated with the concept of soil macro-nutrient contents or soil chemical properties.

The terms soil quality, soil health, and soil condition are usually interchangeable. Sometimes, soil fertility is interchangeable with soil quality to some extent and in some literature (Douglas *et al.*, 1996). Recently, soil quality has come to refer to the *dynamic quality* of soils, defined as the changing nature of soil properties resulting from human use and management. The aims of any policy dealing with sustainable use of soils are to maintain soil quality, properties, processes and diversity. Some management practices, such as the use of cover crops, increase soil organic matter and can have positive effects on soil quality. Other management practices, such as tilling the soil when wet, adversely affect soil quality by increasing compaction. Soil quality evaluation is a tool to assess management-induced changes in the soil and to link existing resource concerns to environmentally sound land management practices. Soil quality assessments are thus used to evaluate the effects of management on soil health. Soil quality provides an integrated method for assessing multiple aspects of the soil and their connections. By linking soil biological, physical, and chemical properties, components and interactions of a soil system are viewed together. This integrated approach leads to more comprehensive solutions, compared to assessing each soil property independently. Soil quality management is a useful and effective approach to resource conservation and best management strategies.

Soil quality is measured by several indicators. These can be soil physical, chemical and biological properties, processes, or characteristics. They can also be morphological or visual features of plants. Indicators are measured to monitor management induced changes in the soil. Some indicators of soil quality are soil organic matter, soil structure, depth of soil and rooting, infiltration and bulk density, water holding capacity, pH, electrical conductivity, extractable N, P and K, microbial biomass carbon and N, potentially mineralizable N and soil respiration (Doran *et al.*, 1996; Larson and Pierce, 1994; Seybold *et al.*, 1998).

The basic goal of a soil quality assessment is to provide information about the trend of soil quality. Results obtained from the first soil quality assessment provide the baseline from which to evaluate future changes. Subsequent measurements provide information about the trend or direction of soil properties. The goal is indicators moving in the desired direction or becoming relatively stable at an acceptable level. Because improvement of soil quality can take many years, further evaluations are critical. A commitment to monitoring the effects of management changes as they relate to attaining soil quality goals helps to demonstrate progress and reveal the need for modifications in the management plan. In most cases, soil properties will not begin to improve for several years, so sampling should be continued to verify that a desired property is either at the same level or improving. Follow-up and evaluation are also needed to ensure that the recommendations for the best management practices are not having negative effects and causing decline in soil quality. Because the goals of soil quality are to sustain productivity, enhance water and air quality, and support human health and habitation, conservation plans developed during this process are responsive and long-term. Over time, plans can be modified to reflect changes in economics, land use and technology.

Continual evaluation is highly recommended to help ensure that the plan remains appropriate and continues to lead toward successful outcomes.

In this study, land use changes were recommended in the tested catchment. In the land unit where the maize planting is unsuitable, sweet chestnut, prickly ash tree or timber pine production was introduced according to site conditions, such as slope, altitude and soil moisture. Unfortunately, these recommendations were not based on integrated land evaluation due to the time limitation of the overall project. The recommendations are formed from discussions with local farmers, agricultural extension technicians and local authorities and are already well accepted in that area. Soil quality assessment was taken as the baseline information and to monitor soil property changes in the future. In terms of erosion control and increasing soil fertility, the indicators measured for the soil quality were soil organic matter, soil structure, depth of soil and rooting, pH, extractable N, P and K, and CEC.

1.5.2 Soil fertility as an indicator for crop production:

There are two unique features of soil quality assessment. One focuses on linkages between soil quality and the health of plants, animals and humans and on farmer-based approaches to assessing soil quality. Another one discerns land use and management impacts on soil quality, develops and synthesizes possible soil quality indices for sustainability, and demonstrates educational tools and techniques to increase knowledge and understanding on soil quality and its role in the biosphere (SSSA, 1996). Lal (1993) described soil quality as:

$$Sq = f\,(Wc, Sc, Rd, Ed, Nc, Bd)t \qquad 1(1)$$

Where: Sq = Soil quality

Wc = Water capacity

Sc = Structural index

Rd = Rooting depth

Ed = Cation exchange capacity (CEC)

Nc = Nutrient supplying capacity

Bd = Soil biodiversity.

In most soils, it may be possible to define soil quality in terms of one or two of the most critical soil properties, e.g., structural index or nutrient capacity. According to Foth and Ellis (1988), soil productivity encompasses soil fertility plus all the other factors affecting plant growth, including soil management. Soil productivity is a measure of the soil's ability to produce a particular crop or sequence of crops under specific management systems. All productive soils are fertile for the crops being grown, but many fertile soils are unproductive because they are subjected to drought or other unsatisfactory growth factors or management practices. There is a strong positive correlation in productive soils between fertility and physical properties so that highly productive soils have desirable physical properties as well as high fertility. The health of an ecosystem is measured not by its short-term biological productivity, but by its ability to sustain biological productivity over time.

By definition (section 1.5.1), soil quality involves more than the capacity of soil to produce crops. The core of soil quality is soil productivity, which is based on soil fertility. The relation of soil quality to crop productivity is probably the best understood of the soil quality components. The ultimate measure of soil health is the ability of the soil to support and sustain plant growth. In this case, if crop yield is our only measure of sustainability, a decline in soil fertility will be concealed by higher crop yields from new varieties and nutrient applications (Wezel *et al.,* 2002).

In most cases, soil chemical properties, such as nutrient content, were measured to evaluate the soil fertility and predict crop yield. In this approach, there is a need to determine critical values for relevant soil parameters. A critical value set for any parameter controlling yield will invariably differ between different soils, farming systems and climate (Powlson and Johnston, 1994). Researches on red soil fertility in China use the criteria in Table 1.9.

In China, 59.1% of cropland is deficient in soil N and P and 22.9% in soil K. Some 50% of soil organic matter contents falls in the 5-20 g/kg range. The proportion of soils with good inherent fertility has decreased from ~33% to just 20% (Li *et al.,* 1997). Zhang *et al.* (1999) reported cultivated soils have limited organic content, nearly 60% of the cultivated land is deficient in P, 30% deficient in K and 14% deficient in both P and K.

Table 1.9. Soil nutrient criteria for evaluating red soil fertility in hilly areas of South-east China.

Soil	Nutrient level	Organic matter (g/kg)	Total N (g/kg)	Total P (g/kg)	Total K (g/kg)	Available P (mg/kg)	Available K (mg/kg)
Non-cultivated	Fertile	>35	>1.75	>1.0	>30	>10	>150
	Slight deficiency	25~35	1.25~1.75	0.6~1.0	20~30	5~10	100~150
	Medium deficiency	15~25	0.75~1.25	0.2~1.0	10~20	2.5~5	50~150
	Severe deficiency	<15	<0.75	<0.2	<10	<2.5	<50
Upland	Fertile	>20	>1.5	>1.0	>30	>10	>150
	Slight deficiency	15~20	1.0~1.5	0.6~1.0	20~30	8~10	100~150
	Medium deficiency	10~15	0.5~1.0	0.2~0.6	10~20	5~8	50~150
	Severe deficiency	<10	<0.5	<0.2	<10	<5	<50

(Source: Zhang *et al.*, 1999)

1.5.3 Soil fertility as an indicator for soil degradation:

Recently, there has been considerable interest in soil quality as a key issue related to agricultural sustainability (Acton and Gregorich 1995; Doran *et al.*, 1994; Papendick and Parr 1992). Soil fertility (chemical properties) may not strongly influence land suitability, since it can be compensated by fertilization, but in terms of environmental protection it (especially the physical parameters) can be a good indicator of the quality of environment or sustainable agricultural production. Land (soil) degradation is examined and measured differently by different specialists, users and donors. In the FAO framework for evaluating sustainable land management, soil quality, soil productivity, soil pH and soil organic matter content are some of the indicators for land sustainable management evaluation (Smyth and Dumanski, 1993).

Spatial variability of soil properties and processes has been a major focus of studies and our knowledge and understanding of these processes have been considerably enhanced. At the same time, several studies have shown that temporal variability of these processes can also be very significant. Van Es *et al.* (1999) showed that tillage and temporal effects were more significant than field-scale spatial variability. Agricultural management practices are a major source of temporal variability of soil properties and processes. Zhang *et al.* (1999) reported that the fertilities of red soil derived from different parent material had different trends under different land use types. Generally, the soil fertility of natural wasteland (undeveloped land) and sparse forestland degraded in most cases. Soil fertility of forestland declined after cultivation as crop upland. Normally, soil fertility increased under paddy field and orchard land with high inputs and management levels. Soil fertility is usually higher in paddy soil than upland soil. The fertility here means the soil nutrient contents which are changing rapidly and frequently with fertilization. It seems that soil physical indicators are more suitable to evaluate land degradation. Land suitability classes decreased in orchard land due to improper agricultural management (Qiu *et al.,* 2002).

To develop soil-quality indices is not a simple task, since soil quality is affected by many properties, and their relative contribution to the index varies from one soil function to another. Soil quality indices must be rather specific for the intended use of soil. The importance of different elements that contribute to a soil quality index will vary from one time to another, and from one location and to another at a given time. Several approaches for assessing soil quality have been proposed. A common attribute among all these approaches is that soil quality is assessed with respect to specific soil functions. People from different disciplines will give their emphasis on different functions. In relation to soil erosion, people emphasize soil fertility decline in terms of chemical and physical properties. The soil lost in the upper reaches of the Yangtze River in Yunnan Province contains 2.72 million t organic matter, 0.2 million t N, 0.34 million t P and 1400 t K and thus decreases soil fertility (Chen 1990). In the USA, Karlen *et al.* (1994), Harris *et al.* (1996) and Mausbach and Seybold (1998) assessed soil quality indices under different conservation measures using quantitative methods. Soil fertility criteria for evaluating red soil degradation by soil erosion are presented in Table 1.10. Currently, there are few threshold values assigned to each property that separates a higher quality soil from a lower quality soil. It is likely that such threshold values would, at a minimum, be soil specific. In addition, it is likely that a single soil could have some measured properties that indicates a higher soil quality while having other measured properties that indicate lower soil quality (Vizcaino, 1996).

The experiments conducted by The Soil Institute of Academia Sinica in eroded red soil areas show that soil fertility can be restored with proper fertilization and management. Soil nutrients and CEC can increase. Available P is the indicator easiest to be increased, then total P, while the total N and organic matter increase slowly. The fertility recovery rate under no-tillage with mulch is higher than under conventional tillage systems (Zhang *et al.,* 1999).

Table 1.10 Soil nutrient indices for evaluating red soil degradation in hilly areas of South-east China

Degradation level	Nutrient level	Total N (g/kg)	Available P (mg/kg)	Available K (mg/kg)
Fertile	Fertile	>2.0	>20	>100
Degradation Ⅰ	Slightly deficient	1.5~2.0	15~20	80~100
Degradation Ⅱ	Medium deficient	1.0~1.5	10~15	60~80
Degradation Ⅲ	Severely deficient	0.5~1.0	5~10	40~60
Degradation Ⅳ	Very severely deficient	<0.5	<5	<40

(Source: Zhang *et al.,* 1999).

1.6. Previous work

This study is a progression of a long-term research programme aimed at improving crop productivity and sustainability on sloping land in South-East Asia. As described before, intensive cultivation of sloping lands using traditional practices and cropping systems is leading to serious erosion in these areas. This coupled with the degradation of both soil structure and fertility, is resulting in an unacceptable decline in production potential. It is therefore imperative that efforts should be made to identify and encourage appropriate technology for managing sloping lands, so that the deterioration and erosion of these lands can be brought under control and the threat to the immediate surrounding areas can be avoided. To realize this goal, conservation farming must be adopted and practised by the farmers who cultivate the sloping lands. Transferring the technologies of conservation farming from experimental plots to farmers is demanded. Different soil conservation technologies are first tested in experimental fields by researchers. After positive results were obtained on a long-term field experiment basis, some of these technologies are validated in farmers' fields. All this was conducted in Yunnan Province. The site descriptions, previous work and findings are briefly outlined here.

1.6.1. General description of Yunnan Province:

1.6.1.1. Geography: Yunnan Province is in south-west China. The Province borders Laos, Vietnam and Myanmar (Burma) and the Chinese provinces of Xizang (Tibet), Sichuan, Guizhou and Guangxi. The Pearl River originates here (Figure 1.4). The Province covers 394,000 km^2 (for comparison, UK is 244,820 km^2 and France is 547,030 km^2). Some 109,800 km^2 belongs to the Upper Yangtze basin (Chen, 1990).

The population of the Province was 40.0 million in 1996. Agriculture is the main activity and source of income of most people. Yunnan is a rural, mountainous and agricultural province in China, which has a high proportion of population under the poverty line. Some 94% of its land is mountainous (Yang, 2001).

Figure 1.4. Location of Yunnan Province

1.6.1.2. Topography: Yunnan is highly varied, with environments ranging from glaciers and snow-capped mountains near the Tibetan border, to tropical forests in Xishaungbanna. Altitude varies from 6740 metres at Mount Kagebo to 76.4 m on the Honghe River, averaging between 1000 and 3000 m. About 95% of land is moderately to steeply sloping, thus only 6.8% of Yunnan's land area can be used for agricultural activities (Thomas, 1992). The land with slopes $<8°$, 8-15°, 15-25° and $>25°$ are 8.87, 13.71, 37.42 and 39.28% of the total land area, respectively (Yunnan Soil Workstation, 1996). Compared with the total uplands in China, Yunnan Province has more steep upland. (Table 1.11). Plate 1.4 shows a typical Yunnan landscape.

Table 1.11 The distribution of upland with different slopes in Yunnan.

Slope degree (°)	0-5	5-8	8-15	15-25	25-35	35-90
Area in China (%)	82.4	3.3	6.6	5.5	1.7	0.5
Area in Yunnan (%)	38.9	8.5	22.2	22.5	6.7	1.2

(Source: Yang, 2001 and 2002)

Plate 1.4 A typical landscape in Huize, north-east Yunnan.

1.6.1.3. Climate: Yunnan has been described as "four different seasons existing simultaneously in one mountain and different weathers beyond 10 km". Yunnan encompasses a wide range of environments, including tropical rainforest, temperate uplands and cool highlands of the Henduan and Gaoligong Mountains, part of the Himalayan range. Climatically, the Province is highly complex, although in general the rainfall can be described as monsoonal (Vogel *et al.*, 1995). The Province is actually influenced by four different branches of the atmospheric circulation, namely the south-west monsoon, the south-east monsoon, the north-east monsoon and the extra-tropical westerlies. Consequently, there is a wide variation in the onset date of monsoon rain throughout the Province and, in fact, it has the greatest variation in any single Asian region. Annual rainfall varies between ~600 mm in dry valleys to 1700 mm in the mountains (Thomas, 1993). Generally, the distinct rainy season is summer and autumn, with >80% of annual rainfall falling between May and September. Winter and spring are very dry and cause problems for crop growth. In Kunming, the onset of rains is generally in May, the rainy season lasting until October, with 75% of annual rainfall occurring during this time. The 30-year mean annual rainfall for Kunming given in 1982 was 1034 mm and the seasonal mean (May-October) 798 mm (Yunnan Meteorological station, 1982).

1.6.1.4. Soils: Diverse natural environments and parent materials increase soil variations. There is a very local complexity along with the altitudinal and latitudinal soil distribution. Most of the soils in Yunnan are, according to the Chinese classification system, Red Earths, which occupies 11.37 million ha and accounts for 32.27% of the total land area (Yunnan Soil Workstation, 1996). Generally, Red Earths have high iron and aluminium contents and low pH, with a medium to heavy texture. They are classified as Ferric Acrisols (FAO/Unesco, 1974), or Ultisols (USDA, 1975). However, in certain sub-groups, such as Cinnamon Red Earths, Ca and Mg accumulate in the surface soil. These soils consequently have a higher pH, with base saturation >40% and are therefore better described as Alfisols, rather than Ultisols (Milne, 2001).

Ultisols are extensive within Yunnan Province and form an important soil resource. However, Ultisols are not naturally as fertile as Alfisols and Mollisols, but they respond well to good management. They are good for crop production. The silicate clays of Ultisols are usually of the non-cohesive type, which, along with the presence of iron oxides and aluminum, assures ready workability. Where adequate levels of fertilizers and lime are applied, Ultisols are quite productive for a wide range of crops.

1.6.1.5. Agriculture: Much of Yunnan Province lies in the China's south-west agricultural region. Most of Yunnan's croplands are located on the central plateau. Agriculture relies on the summer monsoon rains. In this region, the terrain is dominated by hill, with little flat land. Agriculture is poor with extensive systems and low productivity. Grain production is mainly for subsistence. Varying climatic conditions enable a wide variety of crops to be grown. Rice, wheat and maize are the main staples, followed by tubers, legumes and buckwheat. Tobacco, tea, sugar cane, aromatic and oil-bearing plants are grown as cash crops. Cropping systems vary throughout the Province. In some areas, one crop is grown per year, while in others two or three are grown. Yunnan has the greatest number of fruit tree species in China. There is also a significant amount of pastureland, which has potential for the development of animal husbandry.

1.6.2 The development of modified and innovative agricultural techniques in runoff/erosion plots at Yunnan Agricultural University

From 1988-1990, research on ploughing depths, cultivation directions and intercropping on soil erosion and maize yield was carried out on Yunnan Agricultural University (Lat. $25^{o}08'$ N, Long. $102^{o}45'$ E, elevation 1930 m), led by Professors Liu Liguang and Wu Bozhi. This experiment was set up on a upland with 10° slope. The results showed that contour cultivation reduced runoff and soil loss and thus conserved soil organic matter and nutrients and water. In turn, this increased maize yield by 17.6% compared with up-down slope cultivation. Intercropping (with potato) and shallow ploughing (7 cm) were also effective, they increased maize yield by 23.0% and 10.0% compared to monoculture and deep ploughing (20 cm), respectively (Liu *et al.*, 1991). Contour cultivation, shallow tillage and intercropping were recommended for soil conservation and crop productivity increases on sloping land from this experiment.

Commencing in 1990, full field surveys were conducted in diverse environments within Yunnan Province by scientists from The University of Wolverhampton and Yunnan Agricultural University, both in cool montane environments of the upper Yangtze basin (Dongchuan and Huize Counties) and arable subtropical uplands (Kunming District, Chenggong, Lunan, Xundian, Yiliang and Yuanmou Counties). These included the sub-Himalayan system of North Yunnan, the agricultural Central Plateau and especially problematic erosion areas, such as Tu Lin. These surveys led to practical suggestions for integrated multidisciplinary assessments of agro-environmental problems (Fullen *et al*., 1996, 1997, 1998, 1999a, 2000; Barton *et al.*, 1998) and built an invaluable foundation for future research.

In 1993, a formal collaborative project was established between The University of Wolverhampton and Yunnan Agricultural University, to evaluate appropriate agronomic soil conservation measures on sloping red soils in Yunnan Province. This project was jointly funded by the British Council and Yunnan Science and Technology Commission. Cropping treatments of conventional tillage, no-tillage, straw mulch, polythene mulch and intercropping, cultivated both parallel and perpendicular to the contour, were applied to maize (*Zea mays*) grown on 30 erosion plots at three different slope angles (3, 10 and 27°) in Yunnan Agricultural University. These treatments were maintained for each cropping season from 1993 to 1996. Plot data from the 1993-96 cropping seasons (May to October) suggested several soil conservation measures reduced soil loss, compared with current conventional methods. The average rank order of treatment effectiveness in diminishing erosion rates was: 1) straw mulch, 2) intercropping, 3) no tillage, 4) polythene mulch and 5) conventional tillage. The mean erosion rate on the straw mulch plots was 22% of the mean conventional tillage rate. Erosion rates were generally lower on plots where contour cultivation was used. The mean contour cultivation erosion rate was 69% of the mean downslope-oriented rate. Therefore, straw mulch and contour cultivation seem particularly suitable soil conservation measures. In terms of grain yield, polythene mulch exceeded all other treatments, with a 34.8% increase over conventional tillage. Plot results have been published (Wu *et al*., 1996; Fullen *et al*., 1998, 1999a, 2000) and have provided the basis of several research theses (M.Sc. of Xia, 1996 and Ph.D. of Barton, 2000).

Research on the same 30 plots from 1997-2000 confirmed the suitability of straw mulch and contour cultivation as soil conservation measures. The study used a replicated plot design, using the most effective treatments (straw mulch and contour cultivation), with conventional cultivation as the control. To quantify potential erosion rates, there were three bare soil plots, one on each slope class. Data from the 1997, 1998 and 1999 seasons confirm that straw mulch and contour cultivation significantly decreased soil erosion rates and suggested a possible additive interaction between contour cultivation and straw mulch, which increases in effectiveness on steeper slopes. This material formed the basis of the M.Sc. thesis of Zhao Yan (1999) and the Ph.D. thesis of E. Milne (2001). Further progress towards general recommendations required full evaluation of the applicability and effectiveness of techniques developed in plot studies to actual field conditions. This work was conducted in Wang Jia Catchment.

1.6.3. Description of the research catchment: Wang Jia Catchment

Based on several field trips in relevant regions in Yunnan Province, the catchment of Wang Jia, which is affiliated to Kelang village, was selected for research. It was selected due to it being representative for a typical subtropical small watershed in the South-east Asia highlands and providing appropriate opportunities for transportation, management and maintenance.

1.6.3.1 Kelang village: Kelang village is located at Kedu Township, Xundian County, 60 km north-east from Kunming, the capital city of the Province. It is situated at the base of Wang Jia Catchment (Plate 1.5). There were 876 households in 2000. The total population was 3610 (1778 male, 1832 female), among which 51.9% of 1668 labourers were engaged in crop production. Total cultivation land in Kelang is 162 ha, where 99.2 ha is rain fed cropland and 79.2% of land is sloping. The villagers cultivate Wang Jia and other sloping land and neighbouring flat land. Total crop grain yield was 879 tonnes, equivalent to a mean crop per capita of 243.5 kg/year, in 2000.

Cultivated lands in Kelang, like the rest of China, are not owned but allocated for use by farmers. The recent allocation was carried out in 1983, according to the population at that time. Each person was allocated some land in the flat alluvial area, some upland in the semi-mountainous area and some in the mountainous area. In total 0.046 ha of arable land was allocated per person. The per capita land area is very limited and fragmented. This allocation was on the basis of 15-year contracts, but a new agreement was made in 1999 and the cultivation rights were given for 30 years.

Although the agricultural economy at the village scale accounted for progressively less of the total in recent years, especially after 1997, most households are still living on agricultural incomes. Crop production is the first important agricultural activity, with animal husbandry very much behind as second. Normally, crops are sown in two seasons in this region. Rice, maize, beans, potato and tobacco are summer crops and wheat, pea, buckwheat and barley are winter crops. Some green vegetables are cropped all year round. The planting areas and yields of these crops are summarized in Table 1.12. Following the same trend in South-east Asia, rice is the first staple crop for the village, followed by maize in summer and wheat in winter. Tobacco is the key cash crop for Yunnan Province and the village is no exception. But tobacco production is declining drastically since 1997, due to government policy. Consequently the counterpart maize planting area has increased since 1997. The yield of maize is ~5 t/ha. The potential for yield increases is good. The sweet chestnut production is famous in this region and there are sweet chestnut trees planted on sloping uplands. Crop diversity is poor; more cash crops and fruit trees were needed.

Plate 1.5 Wang Jia Catchment and Kelang village

Table1.12. Crops, cropping areas and production totals in Kelang village from 1990 to 2000.

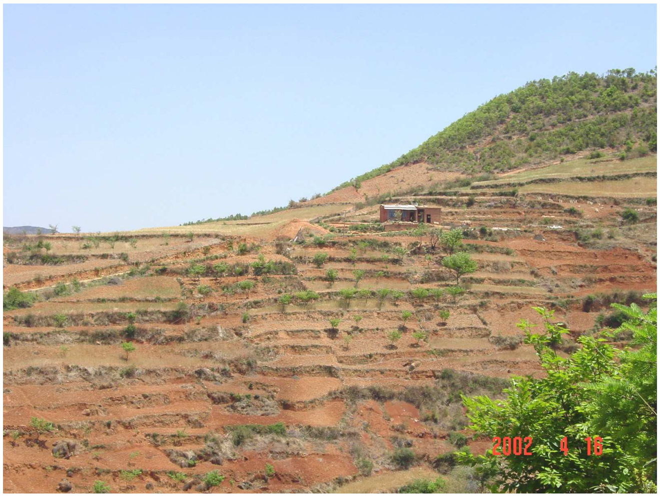
Year	Summer crops								Winter crops				Cash crops		
	Rice		Maize		Potato		Other crops		Wheat		Barley and Pea		Tobacco		Others
	Planting area (ha)	Production (t)	Planting area (ha)	Production (t)	Planting area (ha)	Production (t)	Planting area (ha)	Production (t)	Planting area (ha)	Production (t)	Planting area (ha)	Production (t)	Planting area (ha)	Production (t)	Planting area (ha)
1990	59.33	341.00	34.67	182.00	10.00	50.00	13.33	50.00	70.00	126.00	26.67	24.00	1.60	94.00	0.00
1991	58.67	363.00	26.33	152.00	10.00	32.00	13.33	60.00	70.00	133.00	24.00	29.00	1.93	138.00	0.00
1992	58.07	339.00	14.47	5.00	0.80	3.00	30.67	32.00	70.00	139.00	24.00	30.00	2.00	115.90	0.00
1993	42.53	376.00	14.47	169.00	2.00	12.00	2.67	52.00	68.00	133.00	21.33	38.00	2.53	260.00	0.00
1994	43.33	291.00	14.47	310.00	0.80	4.00	2.67	16.00	68.00	189.00	21.33	45.00	3.00	228.00	0.00
1995	29.33	290.00	14.47	152.00	0.80	6.00	13.33	63.00	61.33	147.00	21.33	44.00	2.93	285.00	0.00
1996	56.00	409.00	12.67	79.30	1.00	28.00	3.33	27.50	61.33	162.00	26.00	74.00	4.93	372.60	0.00
1997	56.00	379.00	10.00	58.00	0.00	0.00	15.00	49.00	65.07	167.00	23.87	76.86	5.12	526.20	6.67
1998	59.00	363.00	33.33	150.00	2.67	15.00	16.00	31.00	61.73	126.00	29.87	72.00	4.80	168.20	2.00
1999	59.00	385.00	33.33	170.00	2.00	16.00	16.00	31.00	61.73	135.00	29.87	78.00	5.20	159.00	8.00
2000	56.67	370.00	33.33	170.00	3.33	19.00	10.33	27.00	55.73	149.00	34.47	49.00	3.27	164.00	2.67

(Source: Kedu Township Yearbook, 2001)

1.6.3.2. Wang Jia Catchment is located at 25°28´18.8˝N and 102°53´06˝E in Kelang. It is a SSW-NNE elongated catchment with a width ranging from 200-345 m and total length is 1930 m. The elevation extends from 1860-2380 m; total elevation difference (relative relief) is 520 m. The mean general slope is 15°. There is a stream running down the catchment, facilitating hydrological studies on sediment loads.

The total area of the catchment is 0.572 km^2, which comprises of 38.9 ha of sloping cultivated land, 1.6 ha of cash crop fruit trees (sweet chestnut), 13.6 ha of forest trees, 0.55 ha of rocky land and 2.5 ha of barren hills. About half the sloping cultivated land is brought under cultivation by local farmers, where the land has a slope angle >25° and an irregular shape (Plate 1.6). The land is very fragmented, separated into several hundreds parcels and belonging to some 100 households. The areas of the smallest parcels are only several square metres. Besides the different physical conditions, land parcels have diverse agricultural management histories, crop productivities and soil fertility.

Plate 1.6. The small and irregular land parcels in the middle part of Wang Jia Catchment



Mostly maize, flue-cured tobacco, potato and legumes (including soybean) are sown in spring-summer and harvested in autumn. Wheat and pea are planted in autumn and winter. Generally, crop yields are low (due to poor cultivation techniques) and water erosion is serious in the catchment. In summer 1998, due to increased total rainfall and an increased frequency of intense storms, serious soil erosion and several landslides occurred (Plate 1.7). In addition, an erosion gully formed, which cut the road in the middle-upper part. Close to the village in the lower part of the catchment, the erosion gully was enlarged to a width of ~10 m and 6-7 m depth, which caused collapse of the arable land and threatened the houses of local people.

Plate 1.7 The large gully in the middle part of Wang Jia Catchment

1.6.4. The evaluation of modified and innovative agricultural techniques in Wang Jia Catchment

Funded by the U.K. Department for International Development/British Council, an evaluation of the effects of modified cropping practices on maize productivity and soil properties was conducted in Wang Jia Catchment. Fifteen plots were established in a randomized block design, with five treatments and three replicates, in 1998. The results showed that contour planting significantly increased crop yields compared with downslope cultivation. Minimum tillage was beneficial for nutrient retention and maintained higher soil moisture when combined with straw mulch. Straw mulch combined with contour cultivation maintained higher soil moisture levels during the dry season, leading to higher grain yields in comparison with unmulched downslope cultivation. Polythene mulch greatly promoted crop growth and led to increased yield. The explanation appeared to be associated with high soil temperatures under polythene mulch. The work formed the basis of the Ph.D. thesis of Huang Bi Zhi (2001) and nine completed Chinese M.Sc. theses.

In parallel with this study, INCOPLAST (Integrated Contour Cultivation, Plastic and Straw Mulch Treatment) system was also evaluated in the catchment from 1999-2001, funded by the European Union (EU). This system combines the best of the techniques identified during the earlier plot trials and is designed to improve yields by the addition of plastic mulch and to conserve soil, water and nutrients by the use of contour cultivation and straw mulch. The results showed that INCOPLAST gave the highest yields in 2000 and 2001. The soil moisture and temperature regimes under polythene mulch made plants grow faster and led to significantly higher grain yields compared with the control. Contour cultivation alone increased yields by 7-11% compared with downslope, equivalent to ~500-1000 kg/ha more grain produced in three years. Economically, contour cultivation plus polythene had the highest net return. Thus, simply replacing downslope cultivation with contour cultivation could contribute to the development of more sustainable cropping systems. Polythene mulch achieved higher yields, but its environmental impact requires further study. Where soil conservation is high priority, INCOPLAST could contribute towards more productive and sustainable cropping systems. The work formed the basis of the Ph.D. thesis of Wang Shuhui (2003) and several completed M.Sc. theses in Belgium, China and Ireland.

In summary, where the risk of soil erosion is higher, or rainfall is likely to be limiting early in the growing season and irrigation water is available for application prior to the application of polythene mulch, the INCOPLAST technique is recommended. Where the priority is to increase maize yields on sloping land under conditions where the risk of soil erosion is low, contour planting with polythene mulch is recommended. Where straw and polythene are not available, simple contour cultivation is recommended for soil erosion control and crop productivity improvement.

1.6.5. Implementation of the modified agricultural techniques in Wang Jia Catchment

The above described plot studies in Yunnan Agricultural University and Wang Jia Catchment funded by British Council provided invaluable preliminary data for the implementation and full evaluation of a new land management plan for Wang Jia Catchment. Improvements in maize cropping practices have been linked to a land management plan to develop a more sustainable agricultural system in Wang Jia Catchment. This has formed a multidisciplinary research project funded by the EU. Early discussions with local farmers, village leaders and local extension workers identified that the installation of an irrigation scheme was a prerequisite for any significant further agricultural development in the catchment, linked to the replacement of some steeper cultivated areas with fruit tree plantations. In parallel to this work and INCOPLAST evaluation, the following land use management options was recommended and implemented in Wang Jia Catchment.

Engineering measures for erosion control, water conservation and irrigation

A substantial programme of engineering works was implemented, involving the construction of dams, gully stabilization measures and irrigation systems. The irrigation systems included five irrigation ponds, served by a large water pond in an adjacent catchment, to store water and to irrigate crops during the dry season. In order to reduce serious, large scale gully erosion and ensure the safety of the road and village during monsoon rainstorms, five barrage dams and three accessory small dams were also established (Plate 1.8). The engineering measures were implemented in early 1999.

Plate 1.8. Dam established across the gully and the water conservation pond in Wang Jia Catchment

Alternative cropping strategies and biological measures for erosion control

On fields where the slope angle was >25°, cultivation was replaced with plantations of cash fruit trees and economic trees. This planting was carried out in the springs of 2000 and 2001. Some 40,000 Chinese pine (*Pinus armandii* Franch) seedlings were transplanted in the upper catchment to fill up the gaps in the woodland, eventually to stabilize slopes and provide a sustainable timber yield. Some 4,100 prickly ash (*Zanthoxylum bungeanum* Maxin) seedlings were transplanted in the arable lands in the upper part of the catchment, to improve soil conservation and provide a cash crop of fruit used for flavourings. Over 15,000 sweet chestnut (*Castanea mollissima* Bl) seedlings have been planted on the steeper slopes of the lower and middle catchment, to eventually replace arable cultivation and provide a valuable cash crop. The trees are still very much at seedling stage. However, the economic study has projected that, once established, the trees will have a positive impact on the local economy. On the fields where the slope angle was 15-25°, grass strips were introduced with contour planting along the field edges, to brake and filter runoff and form ridges naturally. Three grass strips were planted on the eastern interfluve of the middle catchment, where the main arable field in the catchment was located (Plate 1.9). These grass strips were established in Spring 2000.

Plate 1.9. Sweet chestnut, prickly ash and grass strips in Wang Jia Catchment

Cultivation techniques for improving productivities and reducing erosion

The now available cultivated land with slopes <25° will be kept as permanent cultivated land. Maize and soybean were planted as main spring sown crops and wheat as the main winter sown crop. Contour planting, straw and polythene mulch and maize and soybean intercropping were demonstrated in the field trials and recommended to the farmers who are cultivating the sloping lands, to decrease soil and water erosion and increase crop yields. A series of field workshops was held in Wang Jia Catchment, relating to critical times in the cropping season. The first on-farm workshop was held on 12/10/00 for wheat production. Some 40 farmers attended the workshop, in which the results from the field experiments were discussed and improved cropping procedures demonstrated. A further field workshop was held on 25/05/01, focusing on techniques of maize production. The workshop was attended by 45 local farmers. Demonstrations were given of contour cultivation and plastic mulching techniques. The most recent one was held on 20/04/2002, to demonstrate maize planting on the contour and polythene and straw mulching. Plate 1.10 shows the adoption of contour and polythene mulch in the catchment.

Plate 1.10. Contour planting and polythene mulch in the middle of Wang Jia Catchment

In summary, previous work both of the runoff plots at Yunnan Agricultural University and in Wang Jia catchment have shown that contour cultivation, straw mulch and intercropping can reduce runoff and soil loss, and polythene mulch can improve crop productivity. The effective measures developed in the field experimental plots were incorporated into the sustainable land management plan and extended to the whole catchment. This land management plan included engineering, biological and agricultural measures. It was important to evaluate these practices in more plots throughout the catchment, using a farmer-managed approach. Therefore, further evaluation on the measures and follow up of the land use change at the catchment scale were carried out and reported here. The work forms the basis of this Ph.D. thesis and several completed M.Sc. theses in Belgium, enabling the development of a generic land information system which could be generally applicable in subtropical highlands.

1.7 Aims and objectives

The aims of this research are to develop a land information system for the subtropical highland catchment of Wang Jia. This is part of a larger programme of research, evaluation and monitoring contained within and continuing after, the SHASEA project. This is based on a comprehensive survey and description of the biophysical characteristics of the catchment, which provided a baseline for subsequent change. The survey also established the representativity of the catchment in relation to the surrounding area and evaluated the adoption and effectiveness of the sustainable land management measures, developed from the previous work, at the catchment scale.

These aims will be addressed in a series of objectives that are related both to agricultural land use and pedogenesis:

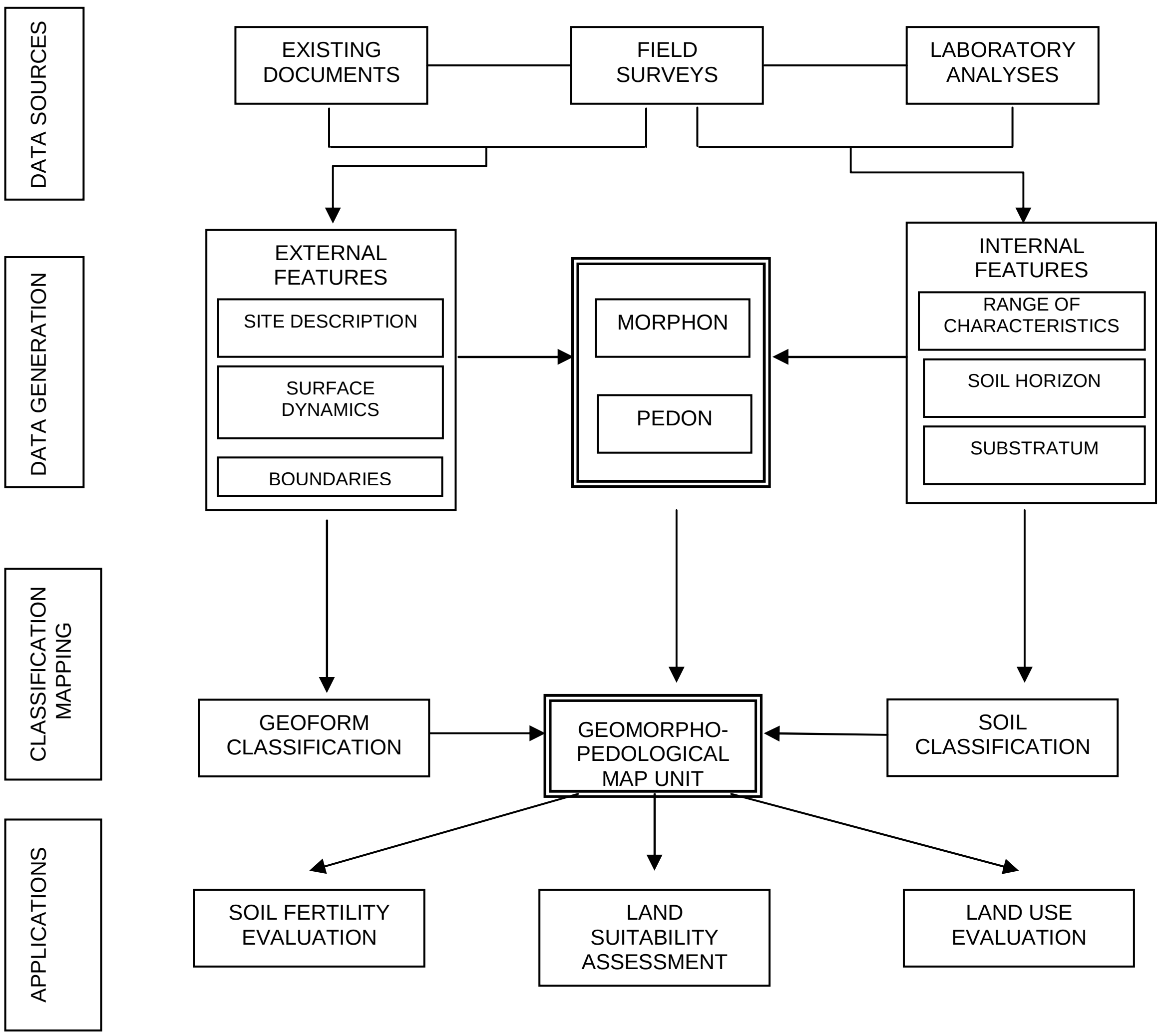
1. To supplement biological survey and meteorological information to a series of field surveys (geological, geomorphological and pedological) and to carry out laboratory analysis of soil chemical properties.
2. To collate, interpret and represent in an integrated form of the results from field surveys and laboratory analysis of soil physical, chemical and mineralogical property geomorphopedologically, using GIS as a tool.
3. To review the assessment of the catchment representativeness in the region, which was carried out initially by SHASEA project co-workers in terms of geomorphological and land cover criteria using air photographs and satellite imagery.
4. To evaluate soil fertility using mainly soil chemical properties and to evaluate maize productivity, using GIS as a mapping tool.
5. To evaluate the effectiveness of selected cropping practices by analyzing the relationship between maize yield and cropping practices.
6. To assess intra-plot variability in soil fertility, compare different soil sampling strategies and suggest a better method for soil sampling specific to local cropping systems.
7. On the basis of the research, to propose cropping practices for the local farmers and to provide a reference information system for the subtropical highland catchment.

This research programme will contribute to the description and evaluation of the land use management strategies that aim at increasing crop productivity in a sustainable and environmentally-friendly way. These land management strategies comprize mechanical and agronomic measures and soil management techniques, leading to the development of a model catchment for further maintenance, training and demonstration purposes. If these land management strategies demonstrate improved crop productivity and sustainability over a long time, their wider adoption will make a contribution to the improvement of food security, poverty alleviation and the development of more sustainable agricultural systems.

Chapter 2. Materials and Methods

In this study, land information was collected through field survey and laboratory analysis, processed and expressed using Geographic Information System (GIS) and statistical analyses. A geomorphopedological approach has been used, which links the soil characteristics of each map unit with geology (rocks as soil parent material) and geomorphology (relief forms). Such ideas suggest a hierarchy of criteria, relations between cause and effect and geomorphopedological balance (Bock, 2002). Since climatic data, soil analysis data and socio-economic parameters can also be included, this kind of information system can be the conceptual basis of a land use/planning tool (Figure 2.1).

Figure 2.1. Conceptual model of land information data structure and geomorphopedological approach.



(Source: modified from Zinck and Valenzuela, 1990)

To be referenced to subtropical highland catchments, the representativeness of Wang Jia Catchment in the region was assessed. Spatial variations at catchment, plot and intra-plot levels were analysed. The outline conceptual work structure of this study is shown in Table 2.1.

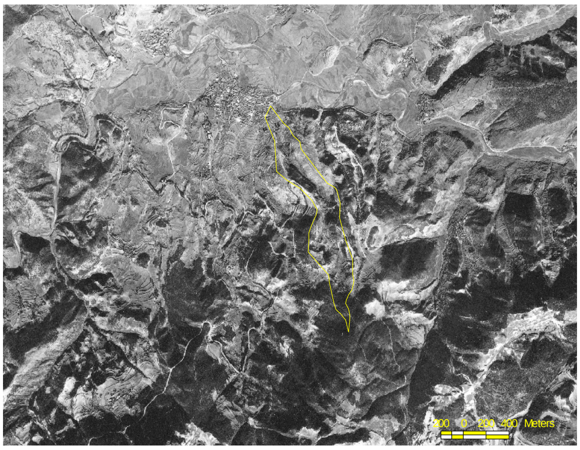
Table 2.1. General description of work structure.

Scale	Tasks
Macroscale	Assess representativeness of Wang Jia Catchment at regional scale.
Mesoscale (a)	Analyse 100 representative plots in Wang Jia Catchment for overview of agro-environment at catchment scale.
Mesoscale (b)	Analyse in detail 30 representative plots (abstracted from 100 plots) for detailed view of catchment agro-environment at plot scale.
Microscale	Analyse intra-plot fertility variability to address the problems of soil sampling with fertility variation on a microscale (pit versus non-pit in a single plot).

2.1 Existing documents and improvement

When research started, there were few accurate and recent documents available for Wang Jia Catchment. There was one topographical map, based on the Beijing Projection System at 1:50,000 scale and with 20 m contours and one set of aerial photographs from 1985 (Figure 2.2). Later, one Spot Multispectral (XI) Scene with ground resolution of 20 m was bought. This satellite imagery was taken in February 1999. To match and synthesize the information from different documents, these documents had to be put into the same co-ordinate system. With a dGPS (differential Global Positioning System) Omnistar LR8, which has an accuracy of 1 m in *x*, *y*, the co-ordinates of some points (e.g. main paths, roads) were taken in the catchment to georeference the topographical map and aerial photographs. The system used was the UTM, zone 48, with the WGS 84 ellipsoid. Further, field surveys were conducted with a simple GPS (30 m accuracy).

Figure 2.2. Original documents of aerial photographes and topographical map of Wang Jia Catchment (1:50,000 scale).



2.2 Field surveys

A series of field surveys were conducted to collect the information and for ground truthing. Land biophysical information was gained through surveys of climate, geology, morphology, biology and pedology.

2.2.1 Ground truthing

Ground truthing is associated with document improvements. In order to georeference and ground truth the existing documents, field surveys were conducted with a dGPS in 1999 and 2000 (Plate 2.1). When the following surveys were conducted, the relevant positions were measured with a portable GPS. Therefore, the information related to the same position could be synthesized by overlaying the different themes.

Plate 2.1. The field survey in Wang Jia Catchment with dGPS.

2.2.2 Meteorological factors

In 1997, a weather station was established on the roof of a farm building in Kelang village, 20m from the catchment base. The weather data were recorded daily at 0900. Precipitation was measured using a tilting syphon rain gauge with a 200 mm diameter drum. The design was based on a tilting Syphon Gauge, produced by the UK Meteorological Office (Shaw, 1988). The chart on the drum was changed daily. Air temperature was recorded automatically using a Casella thermohygrograph and the data were also recorded manually at 0900.

In order to collect accurate weather information for the catchment, an additional automatic weather station (AWS, supplied by Delta-T Ltd, Cambridge, UK) was established in the middle part of the cachment in August 1999 (Plate 2.2). Unfortunately, the data were collected incompletely from the data-logger, so the Kelang weather station data were also used for 1999, 2000 and 2001. In 2002, only the meteorological data of the automatic weather station were used.

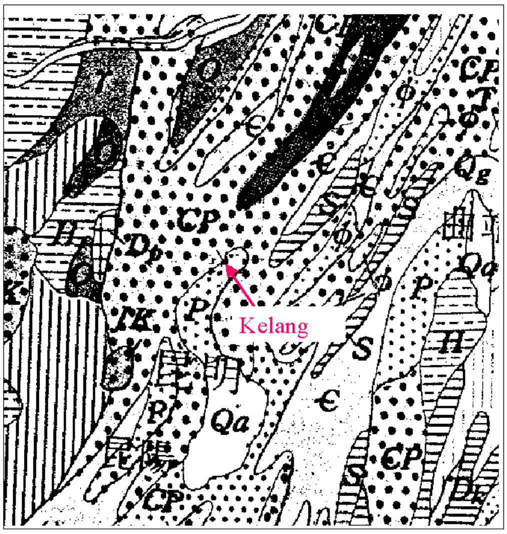
Plate 2.2. A Delta-T weather station and data logger in the middle of Wang Jia Catchment.

At the AWS, rainfall, air temperature, air humidity, wind direction and radiation were automatically recorded. The data were downloaded every 2 or 3 weeks. During the rainy season, the silica gel desiccant in the data logger was checked and replaced if the colour changed from blue to pink, indicating hydration. The daily rainfall, air humidity, air temperature and solar radiation were calculated from these databases from the first day at 0900 to the next day at 0900.

2.2.3 Geological survey

There was no geological map available at a scale appropriate to the small dimensions of Wang Jia Catchment. It was therefore difficult to locate the catchment on a small scale map, such as the geological map at the scale 1:4,000,000 (Figure 2.3) from the Atlas of China (Yang, 1986). A geological survey was carried out in 1999 and 2000 by Daniel Lacroix from Gembloux Agricultural University. The main geological formations were lithologically identified, mapped and sampled for further analysis.

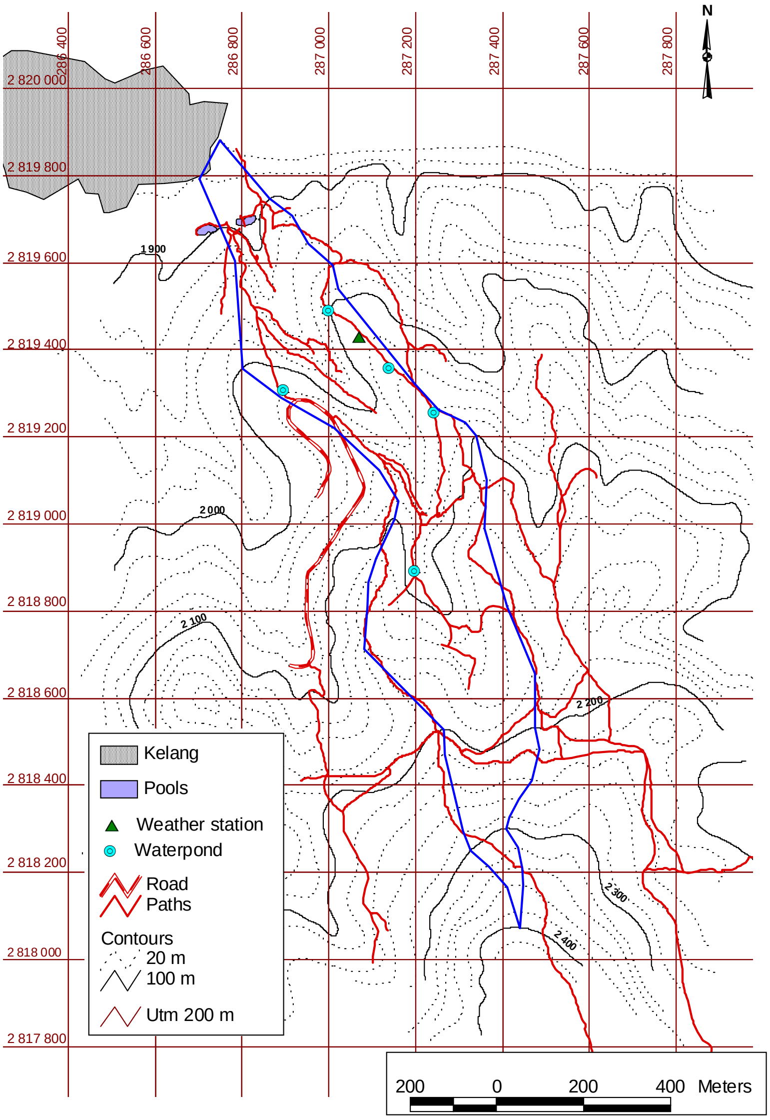
Figure 2.3. Geological map of Wang Jia Catchment (original scale: 1:4,000,000).



2.2.4 Geomorphological survey

The original topographic map was digitized (Figure 2.4). The aerial photos were examined under the stereoscope. Based on the topographical map and aerial photos, the field check was carried out. The altitude was recorded at more positions with a portable GPS, although portable GPS field survey data quality under the specific terrain conditions of mountainous South China needs to be improved (Fan *et al.*, 2000). The digital elevation model was corrected using the elevations taken with the dGPS. The slope map was also produced with ArcView software. Unfortunately, the slope map is produced based on the natural slope, not the true slope in the field, due to terracing. The digitized topographic map was used to develop the digital elevation model and slope map, although the map is rather old.

Figure 2.4. The topographic map of Wang Jia Catchment.



(Source: GAU, 2002).

2.2.5 Biological survey

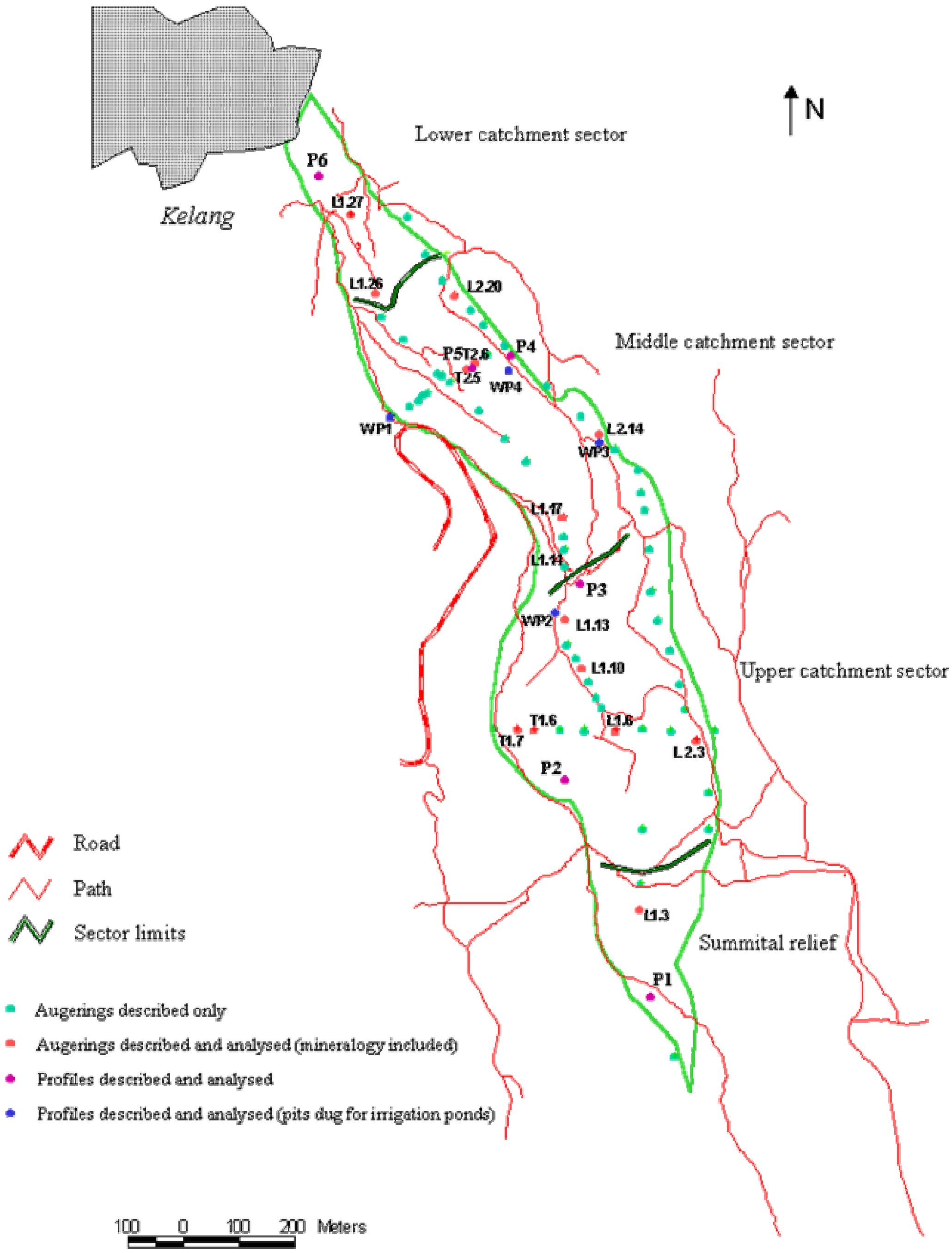
In the catchment, most areas were cultivated by local farmers. Only land areas where slopes were very steep and rocky and the cap of the catchment where the temperature was not high enough for crops, were uncultivated. Therefore, it is difficult to describe the catchment in terms of natural vegetation and biodiversity. A preliminary qualitative vegetation survey was conducted on April 12, 2001. The survey started from the foot of the catchment. The vegetation (shrubs, grasses and trees including some cultivated plants) along a path on the eastern interfluve to the top was identified and sampled for further classification.

2.2.6 Pedological survey

The scope, intensity and scale of the pedological survey were decided by comparison between the data required, as determined by the purposes of the evaluation, and that was already available. The objectives of such survey were to define and determine boundaries of the land mapping units and to determine their land qualities. The delineation of land mapping units was based in part on land characteristics most readily mapped, frequently landforms, soils and vegetation. In this study, soil survey was carried out at a very intensive scale, i.e. plot level.

1. **Augering along toposequences**: In early 1999, 65 hand augerings down to 120 cm where possible, were conducted along four toposequences (Figure 2.5). One longitudinal toposequence along the stream was expressed as L1.1—1.27 in the map. Another longitudinal toposequence along the eastern interfluve was expressed as L2.1—2.23. Both of the longitudinal toposequences were to illustrate the land units related to the main declivity. The other two toposequences were transversal expressed as T1.1—1.7 in the upper catchment and T2.1—2.8 in the middle catchment. All the augerings were described at different depths with texture by hand analysis, colour by Munsell colour chart, and stoniness and pH using a field kit. One quarter of the augerings was sampled, and 41 soil samples were collected. At the same time, taking advantage of the construction of water ponds, four soil pits were described as wp1—4, and 11 soil samples were collected (Figure 2.5). These soil samples from different soil depths were analysed for mineralogy at Macaulay Land Use Research Institute (MLURI), particle size distribution at University of Wolverhampton (UOW) and chemical properties at Gembloux Agricultural University (GAU). The analysis procedures are described in Section 2.4 (Laboratory analyses).

Figure 2.5. The location of pedological observations in Wang Jia Catchment.



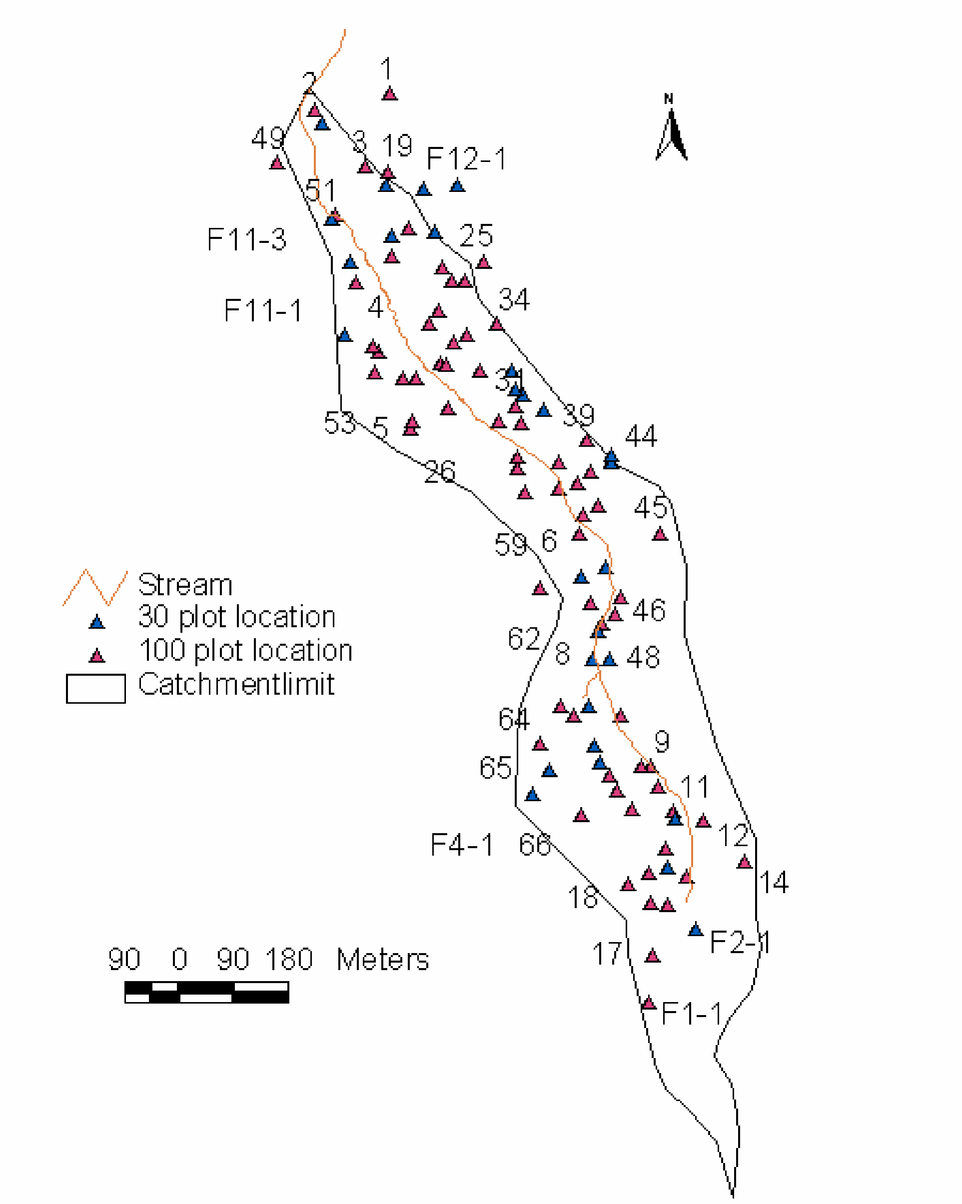
2. **Soil profile description:** Based on the results of augerings, pit descriptions and field observations, 6 main soil types were selected and soil profiles described in detail (P1—6 in Figure 2.5). The description guideline adopted is the one from GAU which results from a Francophone international network for soil data exchange (Table 2.2). At the same time, soil profile samples were taken. These samples were analysed at GAU, UOW and MLURI as previously.

Table 2.2 Soil profile description guidline

			SOIL COLOUR				MOTTLES							STONINESS					STRUCTURE										CONSISTENCE				ROOTS											BOUNDARY to next horizon									
			Munsell				Abundance			Colour						Lithology			Types						Ped size	Ped grade			Soil & ped strength				Abundance of roots				Size (diameter)							Boundary form				Distinctness					
Profile n°	Horizon n°	Depth (cm)	HUE	*	Value	Chroma	< 2 %	2 - 20 %	20 - 50 %	HUE	*	Value	Chroma	% Abundance	Particle-size classes	1	2	3	Massive	Prismatic	Angular blocky	Subangular blocky	Granular	Platy	mm	Weakly developed	Moderately developed	Strongly developed	Loose	Weak	Firm	Strong	Few	Common	Many	Abundant	Very fine < 1 mm	Fine 1-2 mm	Medium 2-5 mm	Coarse > 5 mm	Very fine + fine	Very fine + medium	Fine + coarse	Smooth	Wavy	Irregular	Broken	Sharp	Abrupt	Clear	Distinct	Gradual	Diffuse

3 **30 plots observation:** Based on the augerings, 30 plots were selected as the representative plots (Figure 2.6). To ensure full representativity and appropriate levels of replication, some plots were beyond the catchment interfluve. However, all these plots were within 50 m of the interfluve. More detailed surveys of soil information and crop information were conducted in 1999 to 2001. Sets of composite topsoil samples from these 30 plots were collected in early 1999, late 1999, 2000 and 2001. These composite topsoil samples were analysed for soil fertility evaluation. The samples collected in early 1999 were analysed in Yunnan Agricultural University (YAU). The analysis procedures are described in Section 2.4 (Laboratory analysis).

Figure 2.6. The location of 30 and 100 plots in Wang Jia Catchment.



4 **100 plot observations:** 100 plots were selected to represent the different physical and biological situations all over the catchment in April 1999 (Figure 2.6). These 100 plots included the primary 30 plots. Surveys of the 100 plots were not as intensive as those of the 30 plots. The composite topsoil samples were collected in winter 1999. These samples were analysed in YAU for soil fertility evaluation. The crop yields were measured in 1999 to 2002 to evaluate soil productivity. Plot location and allocation information was surveyed as plot number, plot location with aspect and GPS co-ordinates and altitudes, current land use and planned future land use, name of farmer and allocation status. Basic information on the 100 plots is shown in Table 2.3.

Table 2.3. Basic information for the 100 reference plots in Wang Jia Catchment.

Plot No.	Latitude	Longitude	Owners' name	Altitude (m)	Slope (°)	Slope face	Soil colour	Plot area (m^2)
1	N2528.84176	E10252.79999	Yang Liyong	1879	5.0	NNE	HUE 10 YR 3/4	83
2	N2528.82663	E10252.72660	Sun Guoshou	1898	3.0	NNW	HUE 7.5YR 4/3	118
3	N2528.77707	E10252.77842	Du Rufei	1907	0.0	NNE	HUE 10YR 5/8	81
4	N2528.67342	E10252.77038	Duan Jiangkai	1946	22.7	W	HUE 10YR 4/6	121
5	N2528.59006	E10252.81834	Wu Zhengxue	1960	22.8	NNE	HUE 10YR 4/6	343
6	N2528.49415	E10252.96993	Jiang Xinglong	1914	8.8	NNW	HUE 7.5YR 4/4	323
7	N2528.51829	E10252.96832	Yang Jiazhe	2014	17.8	W	HUE 5YR 4/8	290
8	N2528.39533	E10253.00180	Yang Jiasheng	2038	5.0	NNW	HUE 10YR 4/4	82
9	N2528.25146	E10253.06392	Yang Ligui	2122	8.8	NNW	HUE 5Y 3/2	117
10	N2528.23408	E10253.07100	Wu Jinzhong	2135	6.3	N	HUE 2.5Y 4/4	136
11	N2528.21187	E10253.08645	Du Weichun	2140	2.5	NNW	HUE 2.5Y 4/4	159
12	N2528.20415	E10253.11413	Yu Shurong	2142	18.3	NNW	HUE 2.5Y 4/4	265
13	N2528.15393	E10253.09965	Du Youde	2148	22.5	NNW	HUE 2.5Y 4/2	288
14	-	-	Du Lanxian	2167	32.5	W	HUE 2.5Y 4/6	61
15	N2528.12883	E10253.08130	Du Yande	2163	19.3	NNE	HUE 2.5Y 4/4	116
16	N2528.15747	E10253.06231	Wu Jinzhong	2163	23.5	NNE	HUE 5Y 3/2 & 2/1	311
17	N2528.13012	E10253.06456	Du Yande	2169	24.3	NNE	HUE 5Y 5/3	267
18	N2528.14621	E10253.04235	Zhang Xinglian	2175	24.0	NE	HUE 10Y 4/2	258
19	N2528.77288	E10252.79902	Du Jiachun	1923	9.0	NNE	HUE 7.5YR 6/6	77
20	N2528.76129	E10252.79870	Li Kaixue	1934	1.0	W	HUE 10YR 7/6	79
21	N2528.72364	E10252.82091	Yang Fengxian	1963	23.0	WNW	HUE 7.5YR 6/8	75
22	N2528.68855	E10252.85342	Du Fachun	1992	15.2	WNW	HUE 2.5YR 3/6	149
23	N2528.67664	E10252.86372	Du Fachun	2010	12.8	WNW	HUE 2.5YR 3/6	220
24	N2528.67664	E10252.87659	Yang Xinggao	2006	21.0	WNW	HUE 2.5YR 3/6	203
25	N2528.69499	E10252.89301	Yang Xinggao	1990	12	WNW	HUE 2.5YR 4/6	62
26	N2528.54629	E10252.82477	Wu Zhengxue	1972	26.5	WSW	HUE 5YR 4/8	107
27	N2528.60326	E10252.85471	Wu Zhengxue	1984	24.5	WSW	HUE 5YR 5/8	135
28	N2528.62225	E10252.86565	Wu Zhengxue	1989	33.7	WSW	HUE 5YR 5/6	57
29	N2528.64961	E10252.85052	Jiang Xingwen	1998	11.4	NNW	HUE 5YR 5/8	254
30	N2528.63866	E10252.84280	Yang Jiashou	1999	8.6	WSW	HUE 2.5YR 5/6	148
31	N2528.59714	E10252.89108	Yang Fushuang	2001	12.0	WSW	HUE 2.5YR 5/6	74
32	N2528.62997	E10252.87885	Duan Jizhong	1998	1.5	WSW	HUE 5YR 5/8	51
33	N2528.60165	E10252.85986	Yang Xingyong	2003	9.6	WSW	HUE 2.5YR 4/6	126
34	N2528.63963	E10252.90685	Yang Fushuang	2005	9.7	W	HUE 2.5YR 5/6	99
35	N2528.51217	E10252.92906	Duan Xinghou	2005	19.3	WSW	HUE 5YR 4/8	44
36	N2528.55273	E10252.90942	Duan Xinghou	2013	18.5	WSW	HUE 7.5YR 5/6	104
37	-	-	Duan Xinghou	2018	22.4	WSW	HUE 7.5YR 5/8	49
38	N2528.55240	E10252.93195	Yang Yulin	2018	22.4	WSW	HUE 7.5YR 5/6	79

39	N2528.53792	E10252.99536	Yang Jiahong	2034	15.3	WSW	HUE 5YR 4/8	130
40	N2528.49994	E10252.98667	Duan Guoguang	2033	9.6	WSW	HUE 5YR 5/6	188
41	N2528.50992	E10253.00019	Yang Liyun	2028	16.3	WSW	HUE 7.5YR 5/8	111
42	N2528.47097	E10252.99342	Jiang Xingneng	2025	18.0	WNW	HUE 2.5YR 4/6	122
43	N2528.48031	E10253.00759	Yang Yulin	2034	27.3	WSW	HUE 5YR 5/8	98
44	N2528.52022	E10253.02079	Jiang Xingfu	2040	7.3	WSW	HUE 10YR 6/8	337
45	N2528.45745	E10253.06810	Wu Jiahong	2052	19.7	WNW	HUE 10YR 6/8	80
46	N2528.40080	E10253.03044	Wu Zhengyou	2043	22.0	WNW	HUE 7.5YR 5/4	89
47	N2528.37699	E10253.01403	Jiang Xingwen	2054	20.0	WNW	HUE 5YR 6/6	114
48	N2528.38503	E10253.02529	Yang Jiapin	2063	25.0	WNW	HUE 5YR 5/8	55
49	N2528.77932	E10252.69184	Yang Xingli	1884	0.0	WNW	HUE 7.5YR 4/4	92
50	N2528.69756	E10252.80450	Li Kaixue	1992	19.0	ENE	HUE 7.5YR 5/6	70
51	N2528.73297	E10252.74913	Li Kaixue	1904	22.5	NNE	HUE 7.5YR 5/6	117
52	N2528.61259	E10252.79259	Wu Zhengyou	1962	13.0	NE	HUE 7.5YR 6/6	62
53	N2528.59521	E10252.79033	Yang Jiacang	1966	15.0	NE	HUE 5YR 6/6	67
54	N2528.61774	E10252.78776	Sun Zhuming	1976	13.4	NNE	HUE 5YR 6/6	125
55	N2528.59071	E10252.82960	Jiang Xingzhong	1981	24.0	NNE	HUE 10YR 6/8	167
56	N2528.56496	E10252.86275	Sun Zhuming	1996	17.6	NNE	HUE 10YR 6/8 & 5YR 6/8	130
57	N2528.55144	E10252.82735	Wang Yilin	2010	24.5	N	HUE 7.5YR 6/6	197
59	N2528.49028	E10252.93549	Sun Wenxue	2038	26.3	NNE	HUE 10YR 6/6	323
60	N2528.52183	E10252.92874	Jiang Jinlian	2038	16.0	NNE	HUE 10YR 6/8	97
61	N2528.45649	E10252.99021	Liu Hongbi	2038	20.0	NNE	HUE 7.5YR 5/6	99
62	N2528.40821	E10252.95223	Zou Juying	2065	22.6	N	HUE 10YR 6/6	609
63	N2528.29523	E10252.98731	Wu Hongde	2108	23.0	E	HUE 10YR 5/8	767
64	N2528.30328	E10252.97380	Du Weide	2096	27.3	NNE	HUE 2.5Y 4/6	158
65	N2528.26948	E10252.95513	Yang Ligui	2117	16.7	NNE	HUE 10YR 6/6	121
66	N2528.20736	E10252.99600	Zhao Guangren	2146	27.3	NNW	HUE 2.5Y 4/6	272
67	N2528.29620	E10253.03270	Sun Baocun	2104	13.0	NNW	HUE 2.5Y 5/4	33
68	N2528.24309	E10253.02208	Sun Zhuliang	2124	31.5	NNE	HUE 2.5Y 6/6 & 2.5Y 6/4	430
69	N2528.23022	E10253.03077	Liu Hongbi	2104	19.4	ENE	HUE 10YR 6/4	282
70	N2528.25178	E10253.05330	Li Falin	2129	10.7	NNW	HUE 2.5Y 3/3	182
71	N2528.21348	E10253.04622	Yang Xingbang	2152	24.3	NNE	HUE 2.5Y 5/3	252
72	N2528.17904	E10253.07969	Sun Baochun	2162	22.0	NNE	HUE 2.5Y 4/4	96
F1-1	N2528.04353	E10253.06392	-	2246	22.0	NNW	HUE 2.5Y 4/3	-
F1-2	N2528.08377	E10253.06714	-	2206	8.7	NNW	HUE 10YR 4/4	-
F2-1	N2528.10759	E10253.10995	Li Fayou	2183	18.8	NNW	HUE 2.5YR 4/6	144
F2-2	-	-	Wang Shenfeng	2162	16.7	NNE	HUE 2.5YR 4/3	277
F2-3	N2528.20640	E10253.08806	Du Runde	2136	16.3	NNW	HUE 2.5YR 4/3	214
F3-1	N2528.30489	E10253.00148	Yang Xinghua	2085	5.7	NNW	HUE 2.5YR 4/3	261
F3-2	N2528.34609	E10253.00470	Du Shengde	2076	6.0	N	HUE 10YR 5/8	209
F3-3	N2528.34512	E10253.02208	Huang Jin	2078	5.0	NNW	HUE 10YR 5/4	334
F4-1	N2528.22603	E10252.94837	Du Huaide	2138	19.7	NNW	HUE 7.5YR 5/6	179
F4-2	N2528.24728	E10252.96414	Yang Xinghua	2126	11.7	ENE	HUE 2.5Y 5/4	99
F4-3	N2528.25403	E10253.01339	Du Rende	2104	14.7	N	HUE 10YR 6/4	201
F4-4	N2528.26981	E10253.00824	Du Weide	2118	26.7	N	HUE 2.5YR 6/4	74
F7-1	N2528.37023	E10253.00985	Sun Wenbing	2042	3.3	NNW	HUE 10YR 4/3	159
F7-2	N2528.42655	E10253.01532	Zhang Kaihua	2039	1.7	N	HUE 10YR 5/4	126
F7-3	N2528.41915	E10252.99182	Luo Zhengxue	2036	2.6	NNE	HUE 10YR 4/4	114
F8-1	-	-	Jiao Qifa	-	-	-	-	-
F8-2	-	-	Yang Jiakai	-	-	-	-	-
F8-3	-	-	Jiao Qifa	-	-	-	-	-
F9-1	N2528.51861	E10253.02014	Duan Jixiang	2043	12.4	NNW	HUE 10YR 6/6	609
F9-2	N2528.52472	E10253.02047	Yang Liying	2025	13.0	WNW	HUE 10YR 5/8	276
F9-3	N2528.56335	E10252.95384	Yang Xingpin	2035	8.8	WNW	HUE 5YR 5/6	305
F10-1	N2528.75743	E10252.83411	Du Peiming	1932	4.5	NNW	HUE 10YR 6/6	219
F10-2	N2528.76129	E10252.79870	Liu Hongbi	1929	5.0	NNW	HUE 10YR 6/8	140
F10-3	N2528.81408	E10252.73594	Yang Xingjian	1902	0.0	NNW	HUE 10YR 4/3	138
F11-1	N2528.62708	E10252.75943	Sun Zhuming	1967	10.0	NNW	HUE 7.5YR 5/8 & 5YR 5/8	324
F11-2	N2528.69177	E10252.76426	Zhao Yiming	1934	22.5	NNE	HUE 5YR 5/8	151
F11-3	N2528.73072	E10252.74656	Liu Hongming	1909	21.7	NNW	HUE 2.5YR 5/8	58
F12-1	N2528.76258	E10252.86790	Huang Jin	1983	23.2	NNW	HUE 2.5YR 4/6	349
F12-2	N2528.71591	E10252.80385	Yang Jiahong	1958	18.3	NNW	HUE 7.5YR 6/8	35
F12-3	N2528.71945	E10252.84602	Shi Weiming	1972	19.8	WNW	HUE 7.5YR 5/6	134

5 **Comparison of sampling methods**: The collection and analysis of soil data in an effective and efficient manner at a field or site-specific scale is a scientific and technical challenge. Soil data have become the limiting factor for land use and management practices. Many research results conflict due to different soil sampling strategies. The effect of different soil sampling methods was analysed in this study. Planting pits are used extensively in traditional Chinese agriculture. Typically they are ~20 cm wide and ~15 cm deep pits filled with a mixture of fertilizers and manure. Two sets of soil samples from planting pits and inter-rows in a single plot were collected for comparison of sampling methods in 2001 after maize harvest. Each set consists of 10 samples (Plate 2.3). In this plot, fertilizers and manure were applied to the crop pits before sowing maize. In summary, seven sets of soil samples were collected. Table 2.4 shows the sampling date, number of samples, analysis items and the institutes where the samples were analysed.

Plate 2.3. Soil sampling from planting pits in Wang Jia Catchment.

Table 2.4. Soil samples collected from Wang Jia Catchment at selected times.

Soil sample	Sampling date	Type of samples	No. samples	Analysis items	Analysis institute
Set 1	February, 1999	Horizon	54	Particle size analysis Chemical properties Mineralogy	UOW GAU MLURI
Set 2	February, 1999	Composite	36	Chemical properties	GAU
Set 3	March, 2001	Profile	36	Particle size analysis Chemical properties Mineralogy	UOW GAU MLURI
Set 4	December, 1999	Composite	100	Chemical properties	YAU
Set 5	October, 2001	Composite	30	Chemical properties	YAU
Set 6	October, 2001	Composite	21	Chemical properties	YAU
Set 7	April, 2002	Composite	30	Chemical properties	YAU

2.2.7 Crop survey

The productivity at diverse fertility levels was compared in terms of dry weight. The maize yields in 100 plots were measured and recorded in 1999, 2000, 2001 and 2002. Meanwhile, the survey through farmers' survey cards was conducted. Two sets of winter crop surveys were conducted in 1999 and 2001.

1. **100 plots survey and measurement**. The main crop details measured in the 100 plot fields were maize cultivar, plant density, method of cultivation and planting, general description of crop in terms of size of plants, appearance, level of disease, area sampled and sampled fresh yield. At harvest, whole cobs were harvested, fresh weight recorded from a tested area which were 5-20 m^2 and converted to kg/ha. Meanwhile, samples with different maturity were collected and oven-dried at 78-80^{o}C to give a ratio of dry grain weight to fresh cob weight, which was used to calculate the grain yield. The final yield was expressed in t/ha grain yield with 13% moisture content. The calculation equation is:

   $$\text{Grain yield (kg/ha)} = [(\text{Tested fresh cob weight} / \text{Tested area}) \times 10000] \times \text{Ratio of dry grain weight to fresh cob weight} \times 1.13 \qquad 2(1)$$

2. **30 plots survey and measurement**. In addition to the above items, crop details were measured for the 30 plots in terms of yield components. Ten sample plants from each of the 30 plots were randomly collected and measured to obtain plant height, stem girth and fresh cob, stalk and leaf weight. Additional parameters measured after oven-drying were number of cobs, cob length, cob girth, weight of grains per plant, weight of cob centre and the thousand grain weight.

3. **Winter crop survey in 100 plots**. Wheat and pea were the main winter crops. The main items surveyed were plant species, previous crop, and rates of use of manure and fertilizer, pesticide, labour and irrigation, grain yield and use of the crop products.

2.3 Farmers' survey

In order to understand the farmers' opinion about their own land and farming practices, farmers' survey cards were distributed to and collected from farmers who planted the 100 plots. This survey focused on maize production and was conducted in 1999, 2000, 2001 and 2002. The main items recorded for the 100 plots were maize cultivar, date of sowing, previous crop, method of cultivation, polythene mulch, manure, fertilizer, pesticide, labour, irrigation water used and grain yield at 13% moisture content. In addition, farmers were interviewed to gain comprehensive information on local indigenous knowledge and technologies. In combination, this information supplemented crop field survey data to evaluate productivity, interpret crop growth and yield and assess the acceptance of recommended and modified agricultural practices. This was considered helpful for further technique extension and improvement.

2.4 Laboratory analysis

Laboratory work was jointly carried out at Yunnan Agricultural University (YAU), University of Wolverhampton (UOW), Gembloux Agricultural University (GAU) and Macaulay Land Use Research Institute (MLURI). The author analyzed soil pH, organic carbon, total nitrogen (N), total phosphorus (P), total potassium (K), available nitrogen (N), available phosphorus (P) and available potassium (K) in YAU. The different analytical procedures employed in this study were based on standards specified by the relevant national soil survey authority. Therefore, soil samples for soil fertility assessment in China were analysed using Chinese methods (SHASEA, 2000).

Soil Sampling

<u>Gembloux Agricultural University</u>

On the basis of the soil identification and fertility assessment methodology described in Section 2.2, soil augering and soil profile samples were collected from different horizons. Soil composite samples were collected from 0-15 cm depth, each of them composed of 9 sub-samples taken at random from a 10 x 10 m area. These samples were jointly analysed by people at GAU, UOW and MLURI; therefore sub-samples were transported to these partners.

<u>Yunnan Agricultural University</u>

Several sets of topsoil composite samples were taken in 30 and 100 plots in 1999, 2000 and 2001. These topsoil (0-15 cm) samples were taken in each plot. Some 5 sub-samples were collected and mixed thoroughly, and a sample of ~1 kg taken from this collective bulk was air-dried. The chemical properties of these samples were analysed at YAU.

Soil Preparation

Macaulay Land Use Research Institute

Samples were ground or disaggregated depending upon the type of X-ray powder diffraction analysis to be carried out. For analysis of the bulk soil, samples were ground in a Tema Mill for 2 minutes so that it passed through a 300 mesh sieve. A small portion (2.40 g) of the sample was then transferred to a McCrone Micronising Mill and 0.60 g of corundum added as an internal standard. The samples were then ground in 10 ml of 0.5% polyvinyl alcohol for ~10 minutes. For separation of the clay (<2 μm) fraction ~10 g of sample was thoroughly dispersed in deionised water, further disaggregated using ultrasonics or chemical dispersants where necessary, and washed until a stable dispersion was obtained. The clay fraction was then separated by gravity settling, dried in beakers over a steam bath to a small volume and then freeze-dried.

Gembloux Agricultural University

Air-dried samples were gently broken up in a porcelain mortar and passed through a 2.0 mm sieve for extractable soil nutrients analysis. A sub-sample was then crushed to 0.5 mm in the same mortar for total element analyses.

Yunnan Agricultural University

Air-dried soil samples were ground, sieved and fractionated. Two size fractions of <1.0 mm and <0.25 mm were obtained. The former was used to analyse available soil nutrients and the latter used to determine the total nutrient concentration.

Soil pH

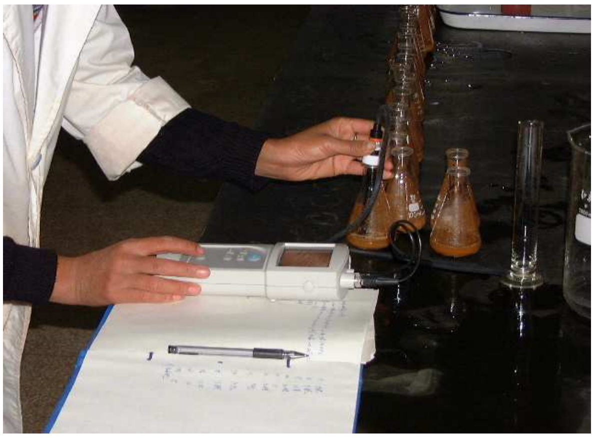
Gembloux Agricultural University

Soil pH H_2O and pH KCl were measured by potentiometry after a 2 h rotative shaking of a 2/5 soil suspension (20 g of <2 mm fine earth with 50 ml of H_2O or 1 N KCl) and a 10 minutes centrifugation at 4,000 rpm. Results in pH units were expressed to 1 decimal place.

Yunnan Agricultural University

Soil pH was measured using a Whatman pH meter. 10 g of air-dried soil with a particle size <1 mm was weighed into a 50 ml glass beaker and 25 ml of distilled water added. The soil and liquid were mixed thoroughly and allowed to stand for 10 minutes. The pH meter was calibrated using buffer solutions of pH 4 and 7, then the pH probe was inserted into the beaker and the soil suspension was stirred by swirling the electrodes slightly. Immediately after, the pH value was read on the standardized pH meter (Plate 2.4).

Plate 2.4. Reading soil pH with a Whatman pH meter at Yunnan Agricultural University.



Soil Organic Carbon

Gembloux Agricultural University

The oxidation of organic matter for a 0.1-1.0 g sample (0.5 mm crushed soil) was performed with 2.000 g $K_2Cr_2O_7$ and 40 ml H_2SO_4 (56%) for exactly 10 minutes heating at 160°C.

$$3C + 2\ K_2Cr_2O_7 + 8\ H_2SO_4 \rightarrow 2Cr_2(SO4)_3 + 2K_2SO_4 + 8H_2O + 3CO_2$$

The excess of $K_2Cr_2O_7$ was then titrated with $Fe(NH_4)_2(SO_4)_2.6H_2O$ 0.1 N (Mohr's salt) in the presence of NaF and diphenylamine (burette of 50 ml graduated at 0.1 ml) and the calculation made by carrying out a blank determination and subtracting the difference. Results were expressed as % with 1 decimal place.

$$K_2Cr_2O_7 + 6\ Fe(NH_4)_2(SO_4)_2 + 7\ H_2SO_4 \rightarrow K_2SO_4 + 6(NH_4)_2SO_4 + Cr_2(SO_4)_3 + 3Fe_2(SO_4)_3 + 7H_2O$$

Yunnan Agricultural University

Organic carbon content was determined by wet oxidation according to the Walkley-Black procedure with heating (Walkley and Black 1934; Nelson and Sommers, 1982). The principle is the same as the procedure employed in GAU, but the procedure is slightly different. Exact 0.100-0.500 g of air-dried soil with particle size of <0.25 mm was weighed into a glass tube. Exactly 10 ml of 0.4 N $K_2Cr_2O_7$-H_2SO_4 was added to each tube. A small funnel was put to cover the opening of each tube. The tubes were placed in a pot containing boiling plant oil with a temperature of ~170-180 °C. When the liquid in the tubes boiled, the time was noted and the liquid was boiled for a further 5 minutes. The tubes were taken out and the solution was transferred into a 250ml flask using about 60-70 ml of distilled water. 2-3 drops of indicator solution were added and the solution was titrated with standard ~0.2 N Fe_2SO_4 expressed to four decimal places. Volume of Fe_2SO_4 used was recorded to calculate the organic carbon %. The equation is:

$$\text{Soil Organic Carbon (\%)} = [(V_0 - V) \times N)] \times 1.13 \times 0.04 / W \times 100\% \qquad 2\ (2)$$

Where: $V_{0:}$ the volume of Fe_2SO_4 used to titrate the blank (ml)

V: the volume of Fe_2SO_4 used to titrate the sample (ml)

N: Normal concentration of Fe_2SO_4 (N)

W: Dry weight of soil (g)

1.13: Calibration factor for oxidation.

The soil organic matter content was not measured directly. It was estimated by assuming total organic matter typically has 58% organic carbon content (Rowell, 1996). Then,

$$\text{SOM \%} = 1.724 \times \text{SOC \%} \qquad 2\ (3)$$

Where: SOM = Soil Organic Matter

SOC = Soil Organic Carbon

Total Nitrogen

<u>Gembloux Agricultural University</u>

Total N was measured according to the regular Macro-Kjeldahl Method (Bremner and Mulvaney, 1982). The digestion of 0.5-2.5 g of <0.5 mm crushed sample was performed until discoloration occurred by heating in a Bucchi tube with 2.5 g of Na_2SO_4, 2.5 g of Selenium (Wieninger's mixture) and 20 ml of concentrated H_2SO_4.

$$OM + H_2SO_4 \rightarrow (NH_4)_2SO_4 + CO_2 + ...$$

After distillation under alkaline conditions, ammonium-N is trapped by H_3BO_3 4% and titrated with HCl 0.1 N (burette of 25 ml graduated at 0.05 ml) in the presence of Tashiro indicator.

$$(NH_4)_2SO4 + 2NaOH \rightarrow Na_2SO_4 + NH_3 + H_2O$$

$$NH_3 + H_3BO_3 \rightarrow NH_4H_2BO_3$$

$$NH_4H_2BO_3 + HCl \rightarrow NH_4Cl + H_3BO_3$$

Results were expressed as % to 2 decimal places.

<u>Yunnan Agricultural University</u>

The method employed to measure total N is the Micro Kjeldahl Method (Bremner and Mulvaney, 1982). The procedure consisted of three main steps:

(a) Digestion: 0.500-1.000 g of air-dried soil with particle size of <0.25 mm was weighed into a 50 ml digestion tube. Some drops of distilled water along with 1.85 g $K_2SO_4.CuSO_4.Se$ mixed catalyst (ratio of 100:10:1,w/w/w) and 5 ml 36 N H_2SO_4 were added and mixed thoroughly. A tiny funnel was put on the opening of the tube. Tube was heated in a far-infrared digestion oven (Plate 2.5). A further 30 minutes boiling was maintained after the solution becomes clear blue-green. The liquid was cooled and graduated to 50 ml with distilled water for distillation.

Plate 2.5. Total N was digested in the far-infrared oven at Yunnan Agricultural University.

(b) Distillation: A 125 ml Erlenmeyer flask containing 5 ml 2% H_3BO_3 with indicator was placed under the condenser of the distillation apparatus to absorb the ammonia. 20 ml of the above described digestion solution was transferred into the apparatus. ~ 20 ml of 10 N NaOH was added to liberate the NH_3. When ~50 ml of distillate was collected, the distillation was stopped.

(c) Titration: Ammonium-N in the distillate was determined along with a blank by titration with 0.02N sulphuric acid. The colour changed at the end point from green-grey to brown-red. Percent N was calculated as follows:

Total N (%) = $[(V-V_0)\ N\times0.014/W] \times 50/20\times100\%$ 2 (4)

Where:

V = Volume of H_2SO_4 used to titrate the sample (ml)

V_0 = Volume of H_2SO_4 used to titrate the blank (ml)

N = Normal concentration of H_2SO_4

W = Dry weight of soil (g)

50/20 = fraction factor for distillation.

Total P and K

Gembloux Agricultural University

Total P was measured by photo-colorimetry after perchloric acid digestion and vanadate yellow complexing.

Yunnan Agricultural University

(a) Ignition: A sample of 0.25 g air-dried soil with particle size of <0.25 mm was weighed into a silver crucible. A few drops of ethanol were added to help diffuse the particles. 2 g of sodium hydroxide was added into the crucible and put in the muffle furnace for 15 minutes at 450^{o}C and another 15 minutes at 720° C (Plate 2.6). 10 ml distilled water was added to dissolve the mixture and the solution was then transferred into a 50 ml volumetric flask. The crucible was washed with 0.4N H_2SO_4 several times until the total volume reached ~40 ml. 5 drops of 1:1 HCl and 5 ml 9N H_2SO_4 were put into the flask. The solution was graduated to 50 ml with distilled water, then filtered and the filtrate was collected.

(b)The determination of K: K in the filtrate is measured using flame photometry (Plate 2.7). Five ml of the filtrate was pipetted into a 50 ml volumetric flask. About 20 ml distilled water was added, the sample was shaken and made up to the mark with distilled water. The mixture was shaken for 10 minutes and K determined using a flame photometer calibrated with standard solutions.

Plate 2.6. Soil sample was ignited in silver crucibles at Yunnan Agricultural University to determine total P.

Total potassium calibration curve

A potassium stock solution was prepared by dissolving 0.1907 g of KCl (previously dried at 110°C) in distilled water and diluting to 1 L. This standard solution contained 100 ppm K and was used to make up a set of standard solutions containing 0, 5, 10, 20, 40, 60 ppm K. The standard solutions were measured at the same time with sample solution to construct the regression curve.

The amount of total K in the soil samples was calculated by the equation:

Total K (%) = $(C \times V \times 10^{-6} \times 50/5 \times / W) \times 100\%$ 2 (5)

Where: C = The estimated concentration of sample solution from the regression curve (ppm)

V = The Volume of the sample solution (ml)

10^{-6} = The constant to transfer μg to g

50/5 = The dilution factor

W = the weight of soil sample (g).

Plate 2.7. The flame-photometer to determine total and available K at Yunnan Agricultural University (supplied by the Shanghai Equipment Company).

(c) The determination of P: 5 ml of the clear solution was pipetted into a 50 ml volumetric flask. ~20 ml distilled water and pH indicator were added. The pH was adjusted using 10% $NaHCO_3$ and 5% H_2SO_4 5 ml of 6.5 N reagent (molybdate-antimony-Vc) was then added. The sample was shaken, made up to the mark with distilled water and allowed to stand for 30 minutes. The P in the solution was measured using a 721 spectrophotometer set at 700 nm at the same time as the standards (Plate 2.8).

Total phosphorus calibration curve

Exactly 0.2190 g monobasic potassium phosphate (KH_2PO_4) was weighed, dissolved and diluted with 1 litre of distilled water. This standard solution contained 50 ppm P. A set of standards was prepared by placing 0, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0 ml standard solutions into 50 ml volumetric flasks. This was followed by addition of 5 ml 6.5 N molybdate-antimony-Vc solution, shaking and making up the solution to the mark with distilled water. Then the solution was allowed to stand for 30 minutes. Percent transmittance was measured at 700 nm and a calibration curve was constructed. The amount of total P in the soil was calculated by the equation:

$$\text{Total P (\%)} = (C \times V \times 10^{-6} \times 50/5 \times / W) \times 100\% \qquad 2\ (6)$$

Where: C = The estimated concentration of sample solution from the regression curve (ppm)

V = The volume of the sample solution (ml)

10^{-6} = The constant to transfer μg to g

50/5 = The dilution factor

W = the weight of soil sample (g)

Plate 2.8. The 721 spectrophotometer used to determine total and available P at Yunnan Agricultural University (supplied by the Shanghai First Laboratory Facility Factory).

Total Carbonates (Ca and Mg carbonates)

Gembloux Agricultural University

This was carried out using a titration method. After reacting 25 ml of H_2SO_4 0.5 N (+ 100 ml of distilled water) with a 1 g soil sample (<0.5 mm crushed soil) and 1 h in a hot water bath, the excess acid was titrated with NaOH 0.5 N (burette of 50 ml graduated at 0.1 ml). The calculation was made by repeating the procedure with a blank and calculating the difference. Results were expressed as % to 1 decimal place.

$$CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + H_2O + CO_2$$

Available Nitrogen

Yunnan Agricultural University

Available N was analysed using a variation of the Conway method (Shi, 1988). All available N was transformed into ammonium, which was then measured by titration in the same way as total N. A sample of 2.00 g of <1.0 mm air-dried soil and 1.00 g of $FeSO_4$ were weighed into the outer ring of the Conway vessel. 2 ml 2% H_2BO_3 with pH indicator was added into the inner ring and 10 ml of 1.8 N NaOH into the outer ring.

The lid was placed on the Conway vessel using glue around the edge to ensure a good seal (Plate 2.9). The Conway vessel was placed in an oven at 40°C for 24 hours. The lid was removed and the solution in the inner ring was titrated with 0.01N H_2SO_4. The volume of acid used in the titration was recorded to calculate the available N content. The calculation equation was as follows:

Available Nitrogen (ppm) $=[(V-V_0)\ N\times14/W]\times1000$ 2 (7)

Where: V= Volume of H_2SO_4 used to titrate the sample (ml)

V_0= Volume of H_2SO_4 used to titrate the blank (ml)

N= Normal concentration of H_2SO_4 (N)

14= one equivalent of N

W= Dry weight of soil (g).

Plate 2.9. Conway vessel with H_2BO_3 in the inner ring and soil sample, $FeSO_4$ and NaOH in the outer ring, used to determine available N at Yunnan Agricultural University.

Available Phosphorus

Gembloux Agricultural University

Available bases (K, Mg, Ca) and available P were measured by Ammonium Acetate 0.5 N + EDTA 0.02 m at pH 4.65 (Na, Fe, Mn, Cu and Zn). Samples of 20 g of <2.0 mm fine-earth and 100 ml of extraction solution were shaken by rotation for 20 minutes. After filtration, Ca, Mg, Fe, Mn, Cu and Zn were measured by atomic absorption

(AAS), Na and K by flame emission (FES) and P by colorimetry using the "vanado-molybdate" reactant. Results were expressed in meq/100g of dry soil with 2 decimal places for K, Mg, Ca and in mg/100g of dry soil with 1 decimal place for P.

Yunnan Agricultural University

Available P was measured using the Olsen method (Olsen and Sommers, 1982). A sample of 2.50 g of <1.0 mm air-dried soil was weighed into a plastic bottle and a spoonful of pure carbon added. 50 ml of 0.5 M $NaHCO_3$ adjusted to pH 8.5 was added. The mixture was shaken for half an hour and then filtered and the filtrate collected. 10 ml of the filtrate was pipetted into a 50 ml volumetric flask and ~35 ml distilled water added and the mixture shaken. 5 ml mixed reagent (molybdate-antimony-Vc) was added and made up to the mark with distilled water. The P content in the solution was measured using a 721 spectrophotometer set at 700 nm (same as in total P). A set of standards ranging from 0-0.5 ppm P was measured at the same time to construct the calibration curve. The equation for available P in the soil was:

$$\text{Available P (ppm)} = C \times V \times 50/10 \,/\, W \qquad 2\ (8)$$

Where: C = The estimated concentration of sample solution from the regression curve (ppm)

V = The volume of the sample solution (ml)

50/10 = The dilution factor

W = Dry weight of the sample (g).

Available Potassium

Yunnan Agricultural University

Available Potassium was measured by using 1 N neutral NH_4OAc as the extractant and measured using a flame photometer. 5.00 g of <1.0 mm air-dried soil was weighed into a plastic bottle and 50 ml of 1N ammonium acetate solution adjusted to pH 7 added. The mixture was shaken for half an hour and then filtered and the filtrate collected. The K concentration in the filtrate was measured using the flame photometer. A range of standards from 0-60 ppm was determined at the same time to construct the calibration curve (as in total K). The equation for soil available K was:

$$\text{Available K (ppm)} = C \times V \,/\, W \qquad 2\ (9)$$

Where: C = The estimated concentration of sample solution from the regression curve (ppm)

V = The volume of the sample solution (ml)

W = Dry weight of the sample (g).

Exchangeable Acidity and Aluminium

Gembloux Agricultural University

The total exchangeable acidity (H + Al) on 50 g of 2.0 mm fine-soil was extracted firstly with 50 ml of 1 N KCl for 30 minutes. This was followed by three successive percolations with the same quantity of KCl. Then the acidity of the solution was measured by titration using 0.1 N NaOH (burette of 5 ml graduated at 0.01 ml intervals).

$$HCl + NaOH \rightarrow NaCl + H_2O$$
$$AlCl_3 + 3NaOH \rightarrow 3NaCl + Al(OH)_3$$

After returning to acid conditions (by one drop of 0.1 N HCl), 10 ml of NaF 4% was added. After effervescence, the solution (and thus indirectly the quantity of exchangeable Al) was titrated with 0.1 N HCl until the red colour of phenolphthalein reappears:

$$Al(OH)_3 + 6\ NaF \rightarrow 3NaOH + Na_3AlF_6$$
$$NaOH + HCl \rightarrow NaCl + H2O$$

The proportion of protons was obtained by difference and results were expressed in meq/100g of dry soil to 1 decimal place.

Macaulay Land Use Research Institute

Exchangeable H and Al were displaced from the soil using neutral 1 M barium acetate. The concentration of ions present in the solution was determined titrimetrically using barium hydroxide solution.

Cation Exchange Capacity (CEC)

Gembloux Agricultural University

A sample of 5 g air-dried soil and 33 ml 1 N NH_4OAC at pH 7.0 were vibrated for 2 hours. The suspension was centrifuged at 4000 revolutions per minute for 10 minutes and this process was repeated three times to replace cations at the soil exchange sites with NH_4^+ (the supernatants were collected for measuring exchangeable bases). The excess NH_4OAC was washed out using concentrated ethyl alcohol. Then NH_4^+ was replaced with NaOH and the supernatant collected. The supernatant was distilled in an alkaline medium and the distillate collected (as described in total N). The distillate was titrated with ~ 0.1 N HCl and the volume of HCl recorded for calculation of CEC. The CEC was calculated as follows:

$$\text{CEC (meq/100g)} = [(V-V_0)\ N/W] \times 100 \qquad 2\ (10)$$

Where:

V = Volume of HCl used to titrate the sample (ml)

V_0 = Volume of HCl used to titrate the blank (ml)

N = Normal concentration of HCl

W = Dry weight of soil (g).

The Effective Cation Exchange Capacity (ECEC) was determined by addition of available cations and acidity data measured separately.

Macaulay Land Use Research Institute

The soil cation exchange capacity was determined by the addition of the exchangeable cation data and the exchangeable acidity data.

Exchangeable Bases (K, Mg, Ca)

Gembloux Agricultural University

The supernatants collected for measuring exchangeable bases were described in CEC measurement. Ca, Mg, Fe, Mn, Cu and Zn were measured by atomic absorption (AAS), Na and K by flame emission (FES).

Macaulay Land Use Research Institute

Cations were displaced from the soil exchange sites using neutral 1 N NH_4OAC. The concentrations of cations present in the solution were determined using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES).

Bulk Soil Mineralogy

Macaulay Land Use Research Institute

(a) Preparation of bulk soils for X-Ray Diffraction (XRD)

Bulk samples were analysed by XRD in a randomly oriented form that was achieved by a spray-drying method. Essentially this method consisted of spraying a sample as an aqueous suspension into a heated chamber, so that it dried in the form of spherical droplets. The suspension was poured into the paint bottle of an air brush and sprayed into an oven pre-heated to 150°C through a hole in the roof of the oven. A large sheet of white paper was inserted beneath the oven and the sample was collected by retrieving the paper. The samples were in the form of thousands of tiny spheres.

(b) Quantitative XRD analysis of bulk soils

Quantitative analyses were made by using a reference intensity ratio (RIR) method on spray-dried soil samples with corundum added as an internal standard. The RIRs of the various minerals present were previously determined from 1:1 mixtures of pure minerals and corundum. Integrated intensities of selected peaks were measured using the Siemens Diffrac AT software package described in the User Manuals. The amount of any phase present was determined by the following equation:

$$Xi = (Xs/RIR) \times (Int\ i/Int\ s) \qquad 2(11)$$

where Xi = weight % component I

Xs = weight % internal standard

Int i = intensity component i

Int s = intensity standard

RIR is the Reference Intensity Ratio

For minerals present in amounts <10%, precision was estimated at ±5% relative. Maximum uncertainty at the 95% confidence level was typically better than ±3wt %. Detection limits were typically <1 wt %.

Clay Mineralogy

Macaulay Land Use Research Institute

(a) Preparation of clay fractions for XRD

Identification and characterization of soil clay minerals relies upon the effective resolution of the basal reflections in the XRD patterns. Most clay minerals have a platy morphology, so that the constituent particles can be made to orient themselves on any flat surface on which they are deposited. In such an oriented form, the basal reflections of the clay minerals are strongly enhanced in the XRD pattern and supplementary techniques can be used to further study the behaviour of these reflections. In this study, a filter peel technique was used to achieve reproducible orientation. This involved filtering the dispersed clay onto an isopore membrane filter using a bench top vacuum pump and a Millipore filtration apparatus, followed by transfer of the filter deposit to a glass slide.

(b) Quantitative analysis of clay fraction

Quantitative analysis of the clay fraction was made by an intensity ratio method, whereby the integrated intensities of selected clay mineral peaks were related to their weight fractions in a mixture by means of a pre-determined proportionality constant termed a mineral intensity factor (MIF). Diagnostic clay mineral peaks were selected and their integrated intensities were measured using the Siemens Diffrac AT software package. Measured peak areas for each mineral identified were divided by the appropriate MIF factor for that peak and the resulting values were totalled and expressed as a percentage of the total. Precision and detection limits were similar to those above. Maximum uncertainty was estimated as <±5 wt% or ±30% relative at the 95% confidence level for phases present in amounts >10 wt%.

(c) Supplementary treatment for clay mineral identification

Detection of expansible clay minerals requires the use of a test based upon the capacity of the mineral to absorb a polar organic liquid into the interlamellar space, so shifting the main basal reflection to a higher spacing. The dry clay specimen was placed in a desiccator over a pool of ethylene glycol and oven-heated overnight at 60°C. After removal from the oven, the specimen was examined again by XRD and compared with the air-dried sample. The effect of heat treatment on the XRD patterns of clay minerals may be diagnostic for the identification of minerals such as chlorite, smectite, vermiculite and various intergrade types. Changes brought by heating occur as a result of dehydration, dehydroxylation or destruction of the clay mineral structures.

Particle size distribution

University of Wolverhampton

The particle size distribution of soils was analysed on fine earth fractions (sieved <2000μm), using a Malvern Mastersizer X laser granulometer (Loizeau *et al.*, 1994). Samples were prepared by oxidizing soil organic matter with hydrogen peroxide. Analysis of the samples was carried out by making a paste using ~2 g of <1.0 mm soil fraction, three drops of Calgon solution (made up by adding 40.0 g of sodium hexametaphosphate to 1 litre of distilled water) to break down the electrostatic bonds between the individual particles and distilled water. Three drops of Calgon were also placed in the granulometer water chamber until an optical density of ~12–14% is achieved, for optimum analysis. During analysis, ultrasonic sound dispersion further broke down possible inter-particle bonds. Two lenses were used to cover the range of sizes in the finely textured soils analysed: the 4-2000 μm lens to cover the larger particles and the 0.1-80 μm lens for accurate analyses of the clay and silt fraction. Reported results from each sample were a mean of three readings. The results from both lenses were blended together using the machine’s software package and then corrected to take account of the previous sieving results, giving a complete particle size distribution in the range 0.1-2000 μm in 32 categories. These were then summed to calculate % sand, silt and clay.

2.5 Maize cultivar description

In the catchment, several hybrid maize cultivars were used. Dian Feng No. 4 (DF4) was recommended by this study for high yielding maize production. Hui Dan No. 4 (HD4) was widely accepted by local farmers before this study (Table 2.5).

Table 2.5 General description of maize varieties of DF4 and HD4

Features	DF4	HD4
Year certified	2001	1992
Recommended planting region with altitude in Yunnan	Middle, north, 1600 -2200 m asl South, 1300 - 1900 m asl	2100 - 2400 m asl depending on the sowing date
Growth duration	120 - 125 days	115 - 120 days
Plant height	~ 227 cm	220 - 250 cm
Cob height of the plant	~ 90 cm	60 - 90 cm
Cob length	~ 18.7 cm	16.2 ~19.2 cm
Cob girth	~ 5 cm	5 –5.2 cm
Rows of grain per cob	14 - 16	14
One thousand grain weight	295 g	320 - 380 g
Plant density	~ 60,000 plants/ha	75,000 – 82,500 plants/ha
Average yield	~ 9150 kg/ha	~ 7125 kg/ha
Soil fertility level	Middle to high	--

(Source: China Maize Production, 2003)

In summary, DF4 was a new cultivar characterized by higher fertility, higher temperature requirements and longer growth duration, leading to a higher yield potential, compared to HD4.

2.6 Statistical analysis and mapping

2.6.1 Statistical analysis

The data were analysed by ‘Minitab 12 for Windows’. The general description data were analysed with descriptive statistics and expressed in means and standard deviations. The regression analysis was carried out for linear models of crop yield with variable soil and other factors. The one-way ANOVA was carried out for different geounits in variable factors. The multivariate analysis of soil data and crop yield was carried out using principal component analysis and afterwards factor analysis to find out the weight value for each factor. The paired-T test was used to compare the soil data of Inter-row and planting pits, the crop yield data of different years and the crop yield of different cultivars.

2.6.2 Mapping

In this study, the land information system was developed as a Geographic Information System. The software used included 'ILWIS (Integrated Land and Water Information System) academic version 3.0' and 'ArcView GIS 3.3'. As a GIS and Remote Sensing package, ILWIS allows the input, management, analysis and presentation of geographical data and is characterized by powerful data processing, while ArcView is a more user-friendly mapping system. The original topographic map, air photographs and data taken by dGPS in the catchment were used to produce a digitized map. This map was georeferenced in the UTM projection system and was used together with field observation data to produce maps (geological, slope, land cover etc.) in ArcView. The 100 plot locations were measured using portable GPS in the UTM system and imported into ArcView. These locations were linked with geounits using 'spatial join' in the ArcView geoprocess function. Therefore, spatial and temporal patterns were assigned for soil properties and crop yield in each map unit. Most maps were then transferred into ILWIS, to enable their use in China. However, the transfer was not successful for polygon maps, due to technical difficulties (i.e. the polygon shape file was not accepted by ILWIS). The satellite images were also imported into ArcView and used for analysis.

Chapter 3. Results

Introduction

In this chapter, catchment representativeness, soil geomorphological information and catchment agrosystems are described and integrated. Soil fertility was evaluated using principal component analysis and factor analysis and intra-plot soil fertility variation was assessed.

Firstly, catchment representativeness is analysed in Section 3.1, including geomorphological criteria and land cover criteria. As soil is a function of climate, parent material, relief, biology and human activities with time, catchment information is presented in such a way to include these soil-forming factors in Section 3.2. Section 3.3 presents catchment agrosystem information including results from the farmers' survey data. Then follows soil fertility evaluation (Section 3.4), which includes screening out the main soil fertility factors using principal components analysis and assigning weight value for each factor using factor analysis. Finally, intra-plot soil fertility variation is analysed (Section 3.5) by comparing soil fertility in pits and inter-rows, which includes soil organic matter, total N, available N, P and K, and pH.

3.1. Catchment representativeness

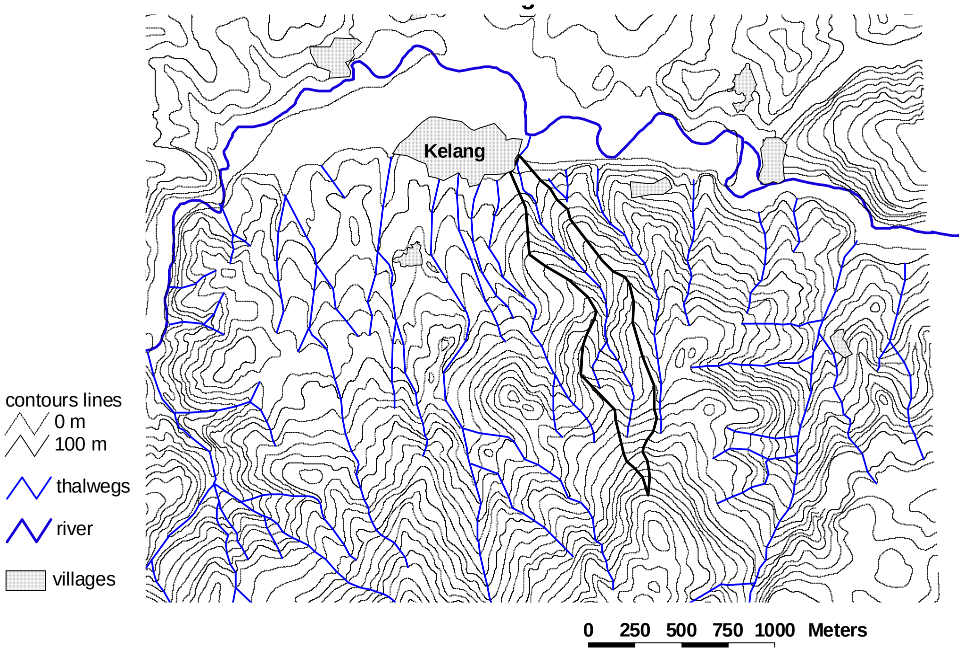
The work involved in this section was mainly conducted by members of the research team from GAU. The author synthesizes and presents it here to integrate available information.

3.1.1 Geomorphological criteria

Wang Jia is a typical catchment in the surroundings of Kelang village (Figure 3.1.1). This area is strongly dissected by small streams, most of which are first or second order streams. Wang Jia is one of several similar small catchments in the south of Kelang village. In order to compare Wang Jia Catchment with other catchments in this area (referred to as the Wang Jia area), hypsometric curves were produced (Figure 3.1.2). Hypsometric curves of Wang Jia Catchment and Wang Jia area have similar patterns. The curves are reasonably parallel between $0<h/H<0.42$ and $0.61<h/H<1$, indicating, in part, similar erosion levels. The median altitude of Wang Jia Catchment is slightly higher (2,100 m) than that of Wang Jia area (2,060 m). This is mainly due to the influence of a pediment remnant in Wang Jia Catchment between 2,100 m ($h/H = 0.46$)

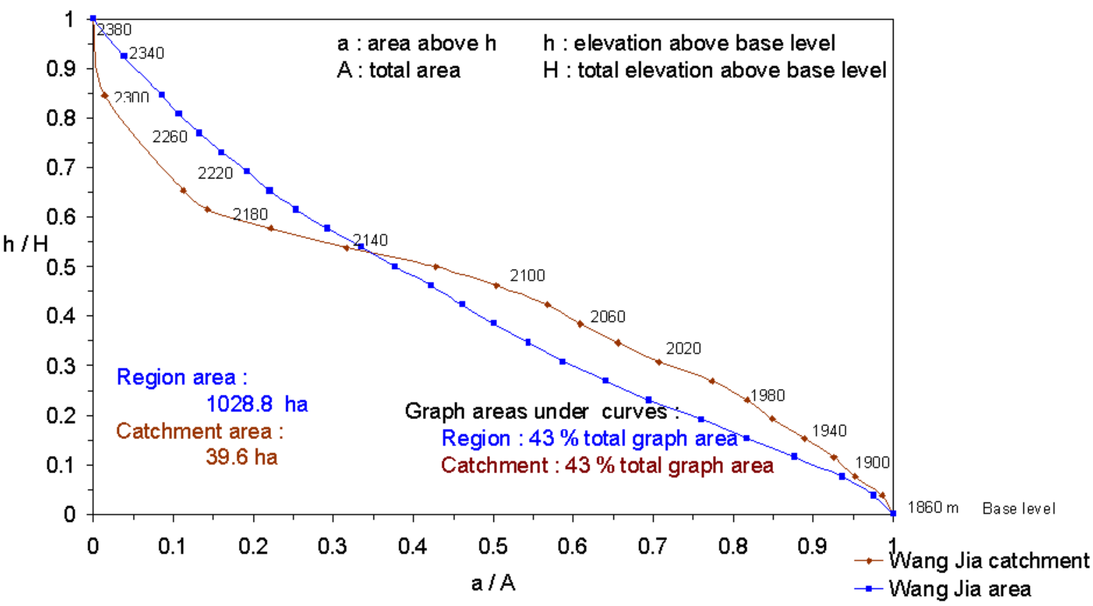
and 2180 m (h/H = 0.61). It is important to mention that these curves are not the actual slope. This is especially true for Wang Jia Catchment, where differences in catchment width have considerable influence on the corresponding relative areas.

Figure 3.1.1. The drainage network of Wang Jia Catchment and Wang Jia area.



(Source: Bock and Lacroix, 2002).

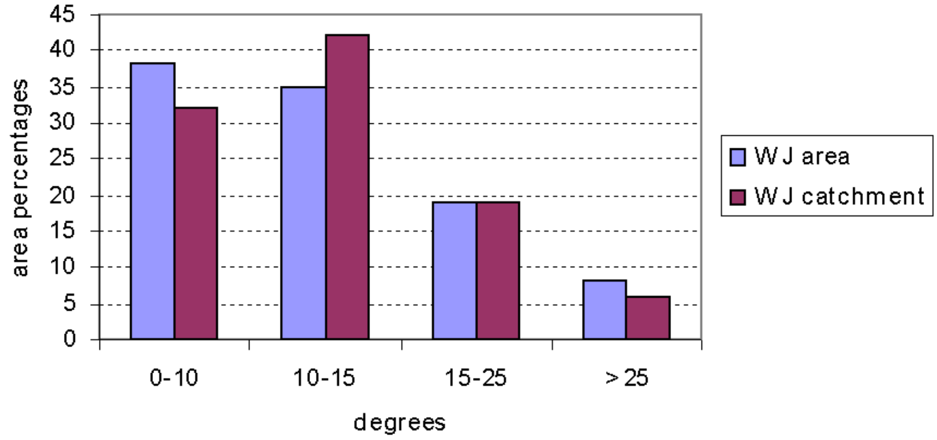
Figure 3.1.2. The hypsometric curves for Wang Jia Catchment and Wang Jia area.



(Source: Bock and Lacroix, 2002).

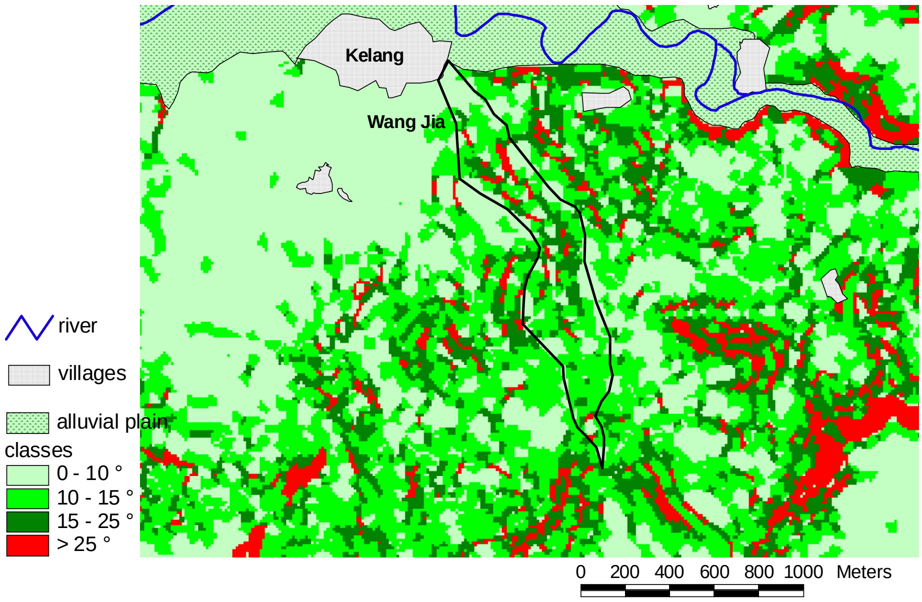
The analysis of natural slopes also showed that Wang Jia Catchment is representative of this area (Figure 3.1.3). The comparison showed a slightly high percentage area of 10-15° in Wang Jia Catchment, which is more sensitive to erosion (Figure 3.1.4). In this area, most slopes are <25°. Only <8% area has a slope >25°, where the cultivated land should be returned to forest or grassland, according to Chinese Government regulations.

Figure 3.1.3. The natural slopes of Wang Jia Catchment and Wang Jia area.



(Source: Bock and Lacroix, 2002).

Figure 3.1.4. The slope comparison for Wang Jia Catchment and Wang Jia area.

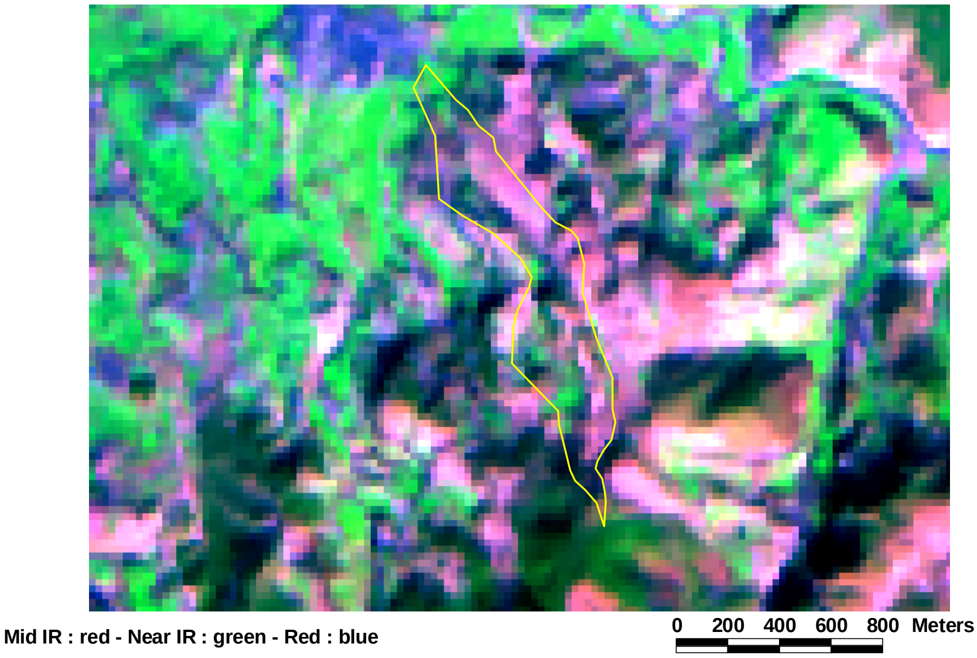


(Source: Bock and Lacroix, 2002).

3.1.2 Land cover criteria

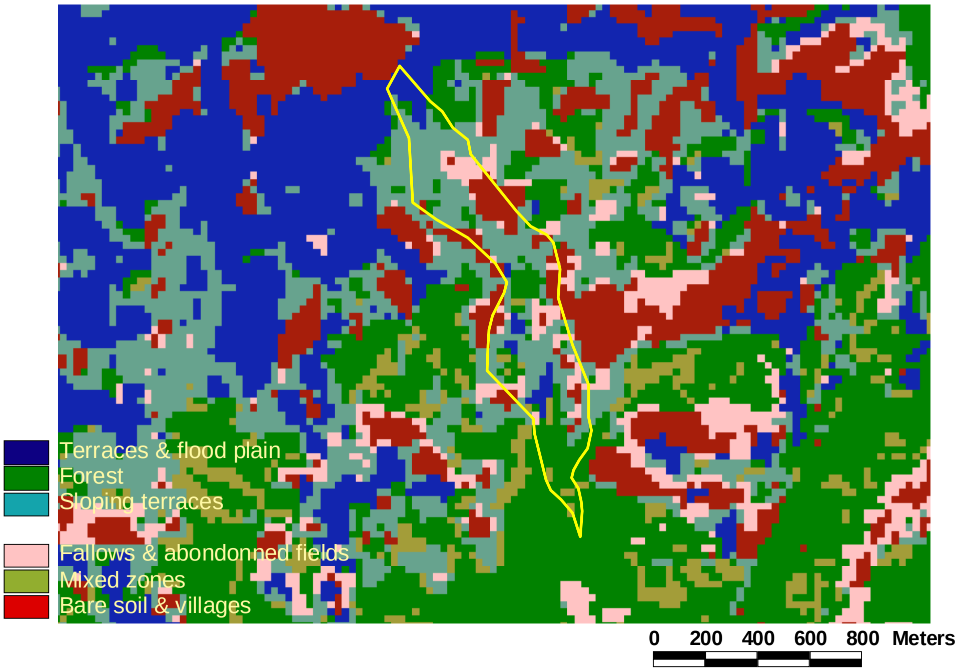
From coloured composites (Figure 3.1.5) and image supervised classification (Figure 3.1.6) it can be concluded that land use in Wang Jia area and Wang Jia Catchment are comparable. A general image of land use was given by coloured compositions (Figure 3.1.5). Mid-infrared band, near infrared band and red band were assigned to red, green and blue, respectively. On this false colour composite, Kelang village (in blue) can be distinguished from some catchment soils (in rose), this distinction impossible to make on classified image (Figure 3.1.6) or on a NDVI (normalized difference vegetation index) map (Figure 3.1.7). The rose colour is due to high reflectances in both red and mid infrared bands. This is the case for soils with little green vegetation cover and which are rather dry (reflectance of mid infrared wave decreases when water content increases). Crops (bright green) and forest on steeper slopes (dark green) are also more easily distinguished on coloured composite maps than NDVI maps.

Figure 3.1.5. Coloured composite of Wang Jia Catchment and Wang Jia area.



(Source: Bock and Lacroix, 2002).

Figure 3.1.6. SPOT image classification of Wang Jia Catchment and Wang Jia area.

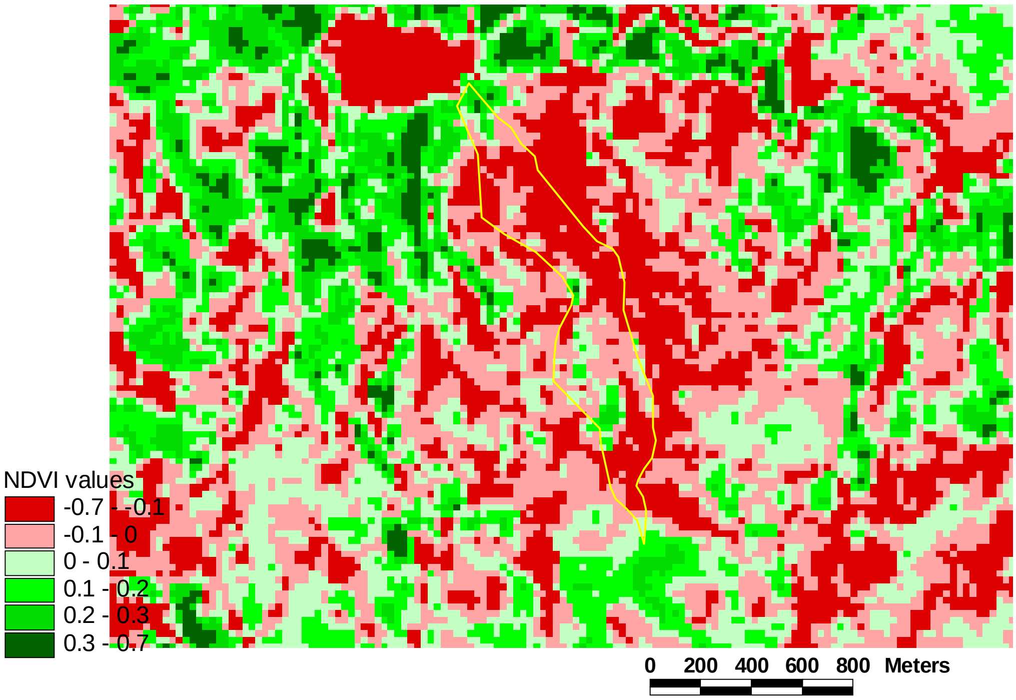


(Source: Bock and Lacroix, 2002).

Catchment representativeness is also confirmed by comparison of NDVI (Normalized Difference Vegetation Index = (near infrared - red) / (near infrared + red)) data (Figures 3.1.7 and 3.1.8). Reflectance in a near-infrared band depends mainly on green vegetation mass, while reflectance in a red band is more soil dependent. Therefore, areas with green biomass have a higher reflectance in a near-infrared than in a red band. Normalized difference vegetation index gives an image of the green biomass density. The greater the value the denser the green vegetation cover (green colour in Figure 3.1.7). It is important to keep in mind that this SPOT image was taken in February 1999, i.e. during the dry winter season (wheat and pea crops).

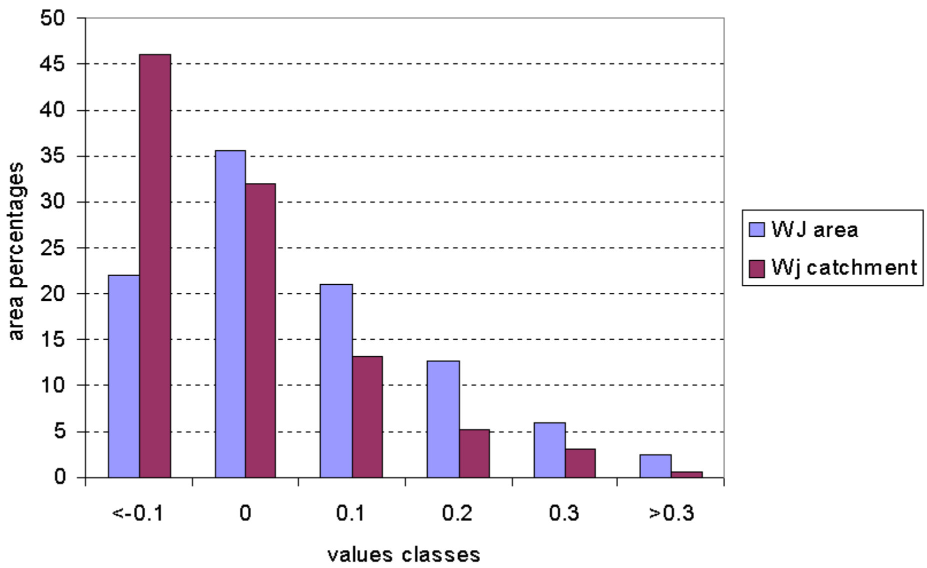
During winter, Wang Jia Catchment has a high percent area with negative NDVI values (red in Figure 3.1.7) indicating less green biomass. An important area of NDVI positive values is the gentle slopes (<10°) situated to the west of Wang Jia Catchment and characterized by NDVI values similar to those in Kelang alluvial plain. That area is not representative of small steep sloping catchments and has a strong influence on the relative percentages of NDVI positive values in the Kelang area (Figure 3.1.8).

Figure 3.1.7. Normalized Difference Vegetation Index of Wang Jia Catchment and Wang Jia area.



(Source: Bock and Lacroix, 2002).

Figure 3.1.8. Comparison of Normalized Difference Vegetation Index for Wang Jia Catchment and Wang Jia area.



(Source: Bock and Lacroix, 2002).

3.2. Geomorphopedological identification

In this study, the geomorphopedological approach was employed, which integrated the geology, morphology and pedology together in the final stage to build up the information systems related to each map unit. This approach started with geology and morphology observation in the field, then added the pedology information afterwards with the soil profile description and laboratory analysis.

3.2.1. Field investigation and description

There are five major factors responsible for soil formation, which are parent materials (geological or organic precursors to the soil), climate (primarily precipitation and temperature), biota (living organisms, especially native vegetation, microbes, soil animals and human beings), topography (slope, aspect and landscape position) and time (the period of time since the parent materials become exposed to soil formation). When attempting to understand geographic variation of soils and how best to use each part of the land, it is often useful to analyse each site in terms of these five soil-forming factors. Additionally, these five factors broaden soil information to land information and are necessary for land evaluation.

3.2.1.1. Climatic/weather condition

Climate determines the nature and intensity of parent material weathering and plant growth. Climate usually influences soil variability at very large scales (regional differences), but where the landscape includes large water bodies, significant hills and mountains, rainfall and temperature may differ greatly over distance of ≤1 km. This is true for Wang Jia Catchment, which has ~520 m difference in altitude within 1930 m distance. The principal climatic variables influencing soil formation are precipitation and temperature, both of which affect the rates of chemical, physical and biological processes (Brady and Weil, 1999). The general weather information of Wang Jia Catchment is summarized in Tables 3.2.1 and 3.2.2. Data in Table 3.2.1 were summarized from both manual and automatic weather station (AWS) data, while data in Table 3.2.2 were summarized from only the AWS, with more parameters.

Rainfall

In 1999, total rainfall was 1028.7 mm and this value is close to the 30 year mean for Kunming, which is 1034 mm (Yunnan Meteorological Station, 1982). Most rainfall was

Table 3.2.1. General climate statistics data of Kelang Meteorological Station, the values are totals / means of data for 1 month.

Year	Parameters	Jan.	Feb.	Mar.	Apr.	May.	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1999	Total rainfall (mm)	74.7	0.0	5.7	5.0	115.6	81.1	292.5	250.3	141.0	20.4	32.9	9.5
	Mean max. air temperature (°C)	15.5	21.1	24.3	26.6	23.1	27.3	26.5	25.9	25.1	23.5	18.4	14.2
	Mean min. air temperature (°C)	-0.8	2.8	5.6	11.2	13.0	17.2	16.5	15.4	13.6	12.1	5.2	1.3
	Mean air temperature (°C)	7.4	11.9	14.9	18.9	18.0	22.2	21.5	20.6	19.4	17.8	11.8	7.8
	Mean 15 cm soil temperature (°C)	7.0	10.2	14.1	19.8	18.4	27.6	20.9	20.1	18.5	17.0	11.7	8.1
	Mean monthly relative humidity (%)	82.0	73.0	47.0	72.0	85.0	85.0	91.0	93.0	92.0	90.0	87.0	85.0
2000	Total rainfall (mm)	4.9	2.3	25.5	0.7	94.3	153.3	130.0	207.2	77.2	79.3	10.4	8.3
	Mean max. air temperature (°C)	15.8	17.2	20.8	24.3	25.2	24.3	26.0	26.0	23.9	22.6	18.3	16.4
	Mean min. air temperature (° C)	-0.5	2.6	4.4	8.9	12.9	15.9	16.1	16.2	14.4	13.0	3.6	1.3
	Mean air temperature (° C)	7.7	9.9	12.6	16.6	19.1	20.1	21.1	21.1	19.2	17.8	11.0	8.9
	Mean 15 cm soil temperature (°C)	6.0	8.2	12.0	16.7	18.9	20.1	20.7	20.4	19.1	16.8	10.6	7.7
	Mean monthly relative humidity (%)	75.0	69.0	65.0	83.0	83.0	96.0	91.0	92.0	90.0	91.0	83.0	80.0
2001	Total rainfall (mm)	1.0	18.3	9.8	0.7	153.1	226.3	154.1	186.7	97.0	14.6*	10.8	0
	Mean max. air temperature (°C)	17.8	17.3	18.8	27.0	23.1	24.1	27.7	26.5	24.5	19.0*	16.1	15.6
	Mean min. air temperature (°C)	0.8	1.8	2.9	8.9	12.3	14.3	17.5	16.7	16.3	13.9*	6.1	3.5
	Mean air temperature (°C)	9.3	9.6	10.9	18.0	17.7	19.2	22.6	21.6	20.4	16.5*	10.3	9.0
	Mean monthly relative humidity (%)	72.0	70.0	66.0	62.0	65.0	74.0	89.0	87.0	89.0	91.0*	74.4	64.7

Note* the first week only of October 2001. 1999 and 2000 data were from the manual weather station, while the 2001 data were from both the manual and automatic weather station. Data adapted from Wang (2003), except for November and December 2001.

Table 3.2.2. Monthly weather information for Wang Jia Catchment summarized from the 2002 Automatic Weather Station data.

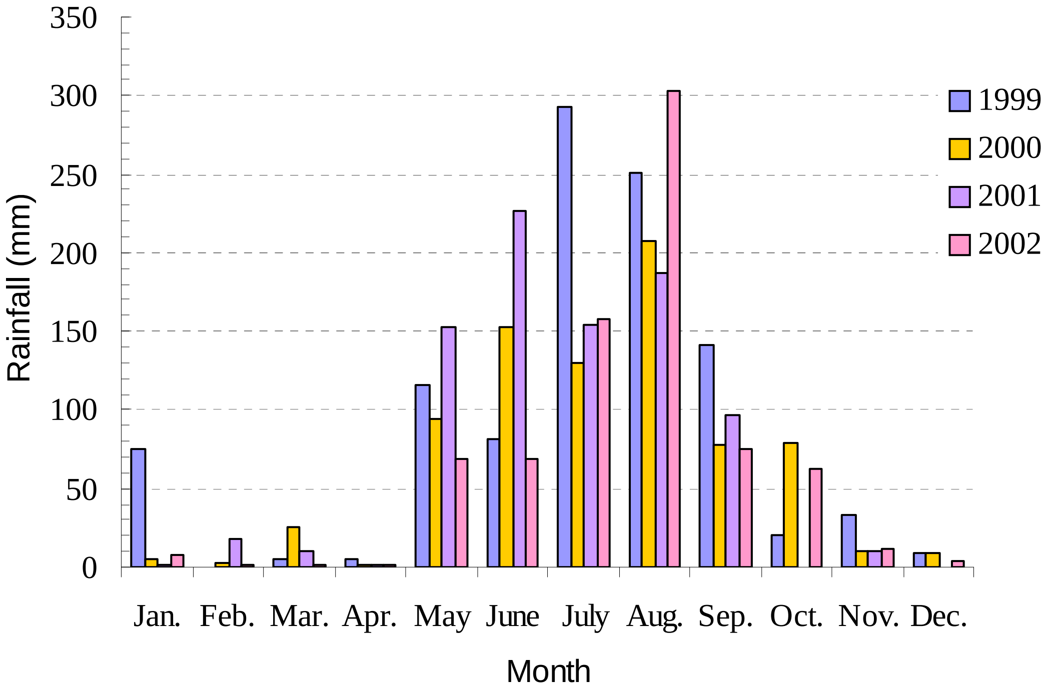
Parameter		Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
Rainfall (mm)	Total	7.2	1.2	1.6	0.8	68.4	68.8	158	302.4	75.2	62.0	11.2	3.2	63.3
Radiation (kwm^{-2})	Max.	0.85	0.83	0.93	0.89	0.99	0.98	1.07	1.08	0.92	0.84	0.81	0.70	
	Mean	0.13	0.17	0.17	0.22	0.16	0.16	0.14	0.13	0.14	0.14	0.11	0.13	0.15
	Min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Air temperature (^oC)	Max.	17.9	22.2	25.3	28.1	27.9	29.8	29.0	28.5	27.7	25.0	24.9	21.2	
	Mean	8.5	12.1	14.2	17.7	18.0	21.1	19.6	18.0	16.8	15.4	11.9	9.6	15.3
	Min.	0.1	0.5	0.0	6.2	11.0	14.8	12.1	9.4	8.8	5.2	4.8	0.5	
Soil temperature at 15 cm depth (^oC)	Max.	12.8	17.2	20.1	25.0	25.4	26.0	25.7	24.6	24.0	20.5	18.3	15.2	
	Mean	9.3	11.8	14.2	18.8	19.5	21.8	21.3	20.0	19.2	17.0	13.5	10.6	16.4
	Min.	6.8	7.0	8.3	13.7	16.2	18.9	18.0	16.4	15.3	14.2	9.5	5.9	
Wind direction (deg)	Max.	190	184	192	193	192	194	194	93	193	191	191	192	
	Mean	169	166	168	168	170	171	171	69	170	172	173	172	161
	Min.	102	100	101	103	106	107	108	0	106	100	106	108	
Relative humidity (%)	Max.	100	93	99	88	100	100	100	100	100	100	100	98	
	Mean	63	50	48	39	67	77	85	85	78	76	74	64	67
	Min.	20	17	15	8	16	31	30	25	36	27	28	19	
Wind speed (m/s)	Max.	9.7	9.9	10.9	10.4	7.6	6.7	4.2	4.4	4.2	4.8	6.7	8.6	
	Mean	2.6	2.7	3.0	3.8	1.9	1.6	0.9	0.8	1.0	1.0	1.8	2.1	1.9
	Min.	0.1	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Originally, rainfall was recorded every ten minutes, the other parameters every thirty minutes. Data presented here excludes 11/04/02 00:54 to 28/04/02 11:48; 27/05/02 13:33 to 11/06/02 11:35 and 15/06/02 22:48 to 19/06/02 11:39, due to problems with the data logger.

concentrated in May, July, August and September (Figure 3.2.1). January also had more rainfall in 1999, but in February little rain fell in all years. Total rainfall in 2000 was 793.4 mm and this was less than the 30 year mean. More rain fell from May to October. In 2000, April was a very dry month. The rainfall in 2001 had a similar trend to 2000, the total rainfall was 857.8 mm (excluding 07 October to 31 October), a little more than 2000 and the driest months were January and October. Due to the incomplete data, total and monthly rainfall in 2002 were the lowest in four years. Another responsible factor may be the different measuring method of rainfall; 2002 data were simply from an automatic weather station. However, August 2002 had the highest monthly rainfall among the four years, which caused mudflows in the middle catchment and blocked the main path.

Figure 3.2.1. Monthly rainfall distribution during 1999-2002*

(Data for October 2001 and April, May and June, 2002 are incomplete)

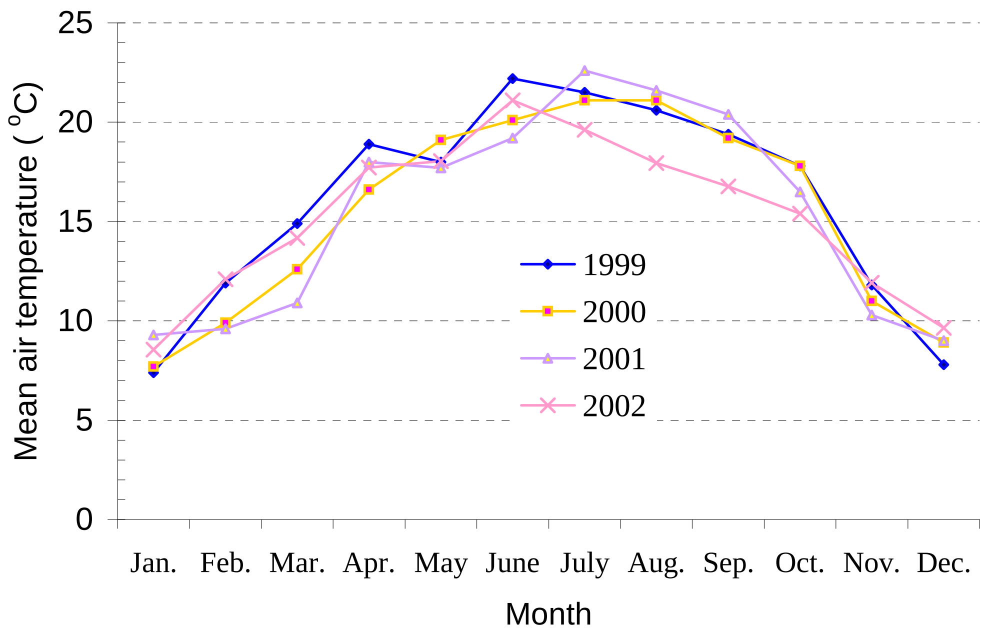


For the crop, the monthly rainfall totals and distribution during the cropping season are much more important than the whole year. Rainfall in 1999, 2000, 2001 and 2002 shows there was a relatively even rainfall distribution in 2000 and the maize cropping season rainfall occupied 82.2% of the total year's rainfall. A very changeable pattern was found in 1999 and little rain fell ~40 days after seeds were sown. This stage was crucial for early crop development and growth. In 2001, more rain fell in the crop early stage and the distribution was relatively even. Unfortunately, an unexpected heavy hail storm (09 August) influenced final yields considerably.

Temperature

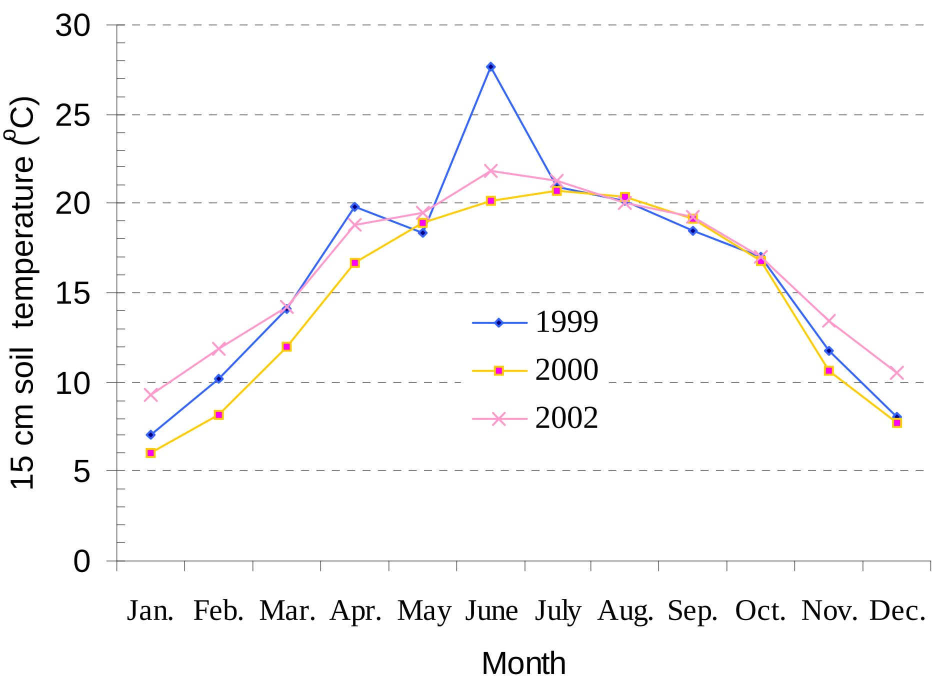
Geographically, Wang Jia Catchent is situated in the subtropical humid region. Due to the relatively high altitude, the temperature is similar to temperate regions. The mean air temperature was calculated from air maximum and minimum values (Table 3.2.1). During the recorded period, the extreme maximum temperature in 1999 was observed on three days (April 24, May 4 and July 24), at 31.5°C. The extreme minimum temperature was –7.5°C, which was recorded on December 25 and in the following four days the temperatures remained <-5°C. In 2000, the extreme maximum temperature was on July 28 (32.2°C) and the extreme minimum temperature was –5.0°C, recorded on January 1 and 6. In 2001, the maximum temperature was also 31.5°C, recorded on June 19 and July 21 and the extreme minimum temperature was –3.5°C, recorded on January 12.

Figure 3.2.2. Monthly air temperature during 1999-2002.



For the monthly mean air temperature, the pattern of four years was similar (Figure 3.2.2). From January to June or July or August, the temperature increased each month, then after August the temperature decreased slowly and it became progressively colder. December and January were the coldest months. Little difference was found between the different years. In 1999, the warmest month was June and in May the mean air temperature was lower than in April. This was probably affected by rainfall, usually little rainfall occurs in April and the rainy season started in May. Few rainfalls in June also made the air temperatures higher, due to little cloud cover. In 2000, the air temperature curve pattern was relatively smooth and near four year mean air temperature. In 2001, January was relatively warm, but February and March were cold months compared with 1999 and 2000. The remaining months nearly followed the pattern of 1999, the warmest month in 2001 was July. In 2002, July to October were relatively cold compared to 1999, 2000 and 2001.

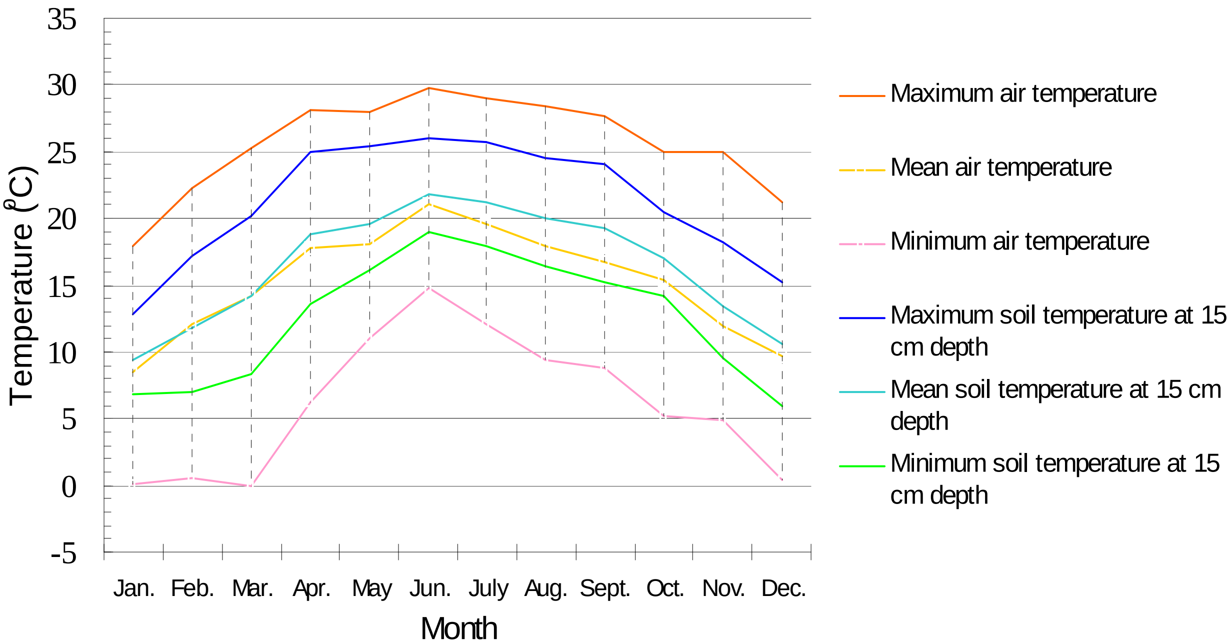
Figure 3.2.3. Monthly mean soil temperature at 15 cm depth in 1999, 2000 and 2002.



Soil temperature at 15 cm soil depth in 1999, 2000 and 2002 is shown in Figure 3.2.3. The pattern of soil temperature followed the similar trends as air temperature. Generally, soil temperature increased from January to June or July, then decreased from August to December. January had the lowest soil temperature in the whole year. This trend was true for all the three years. The soil temperature was unusually high in June 1999, at 27.6°C. This temperature was higher by 7.5°C compared to the 30 year mean. Soil temperature in 2000 and 2002 had a smooth pattern, with 2002 slightly warmer than 2000.

Another feature was the large temperature difference between monthly maximum and minimum air temperature, which was related to daily temperature differences and can affect crop carbohydrate accumulation. The temperature difference between different seasons was not so great (Figure 3.2.4). The largest difference between monthly mean air temperatures was between June and January 2002, at 12.6°C. The difference between monthly maximum and minimum air temperature reached 25.3°C in March 2002. Soil temperature was relatively stable and the differences were not so large compared to air temperature. The biggest difference between monthly mean soil temperatures was between June and January, at 11.8°C. The difference between monthly maximum and minimum soil temperature was 12.5°C in March.

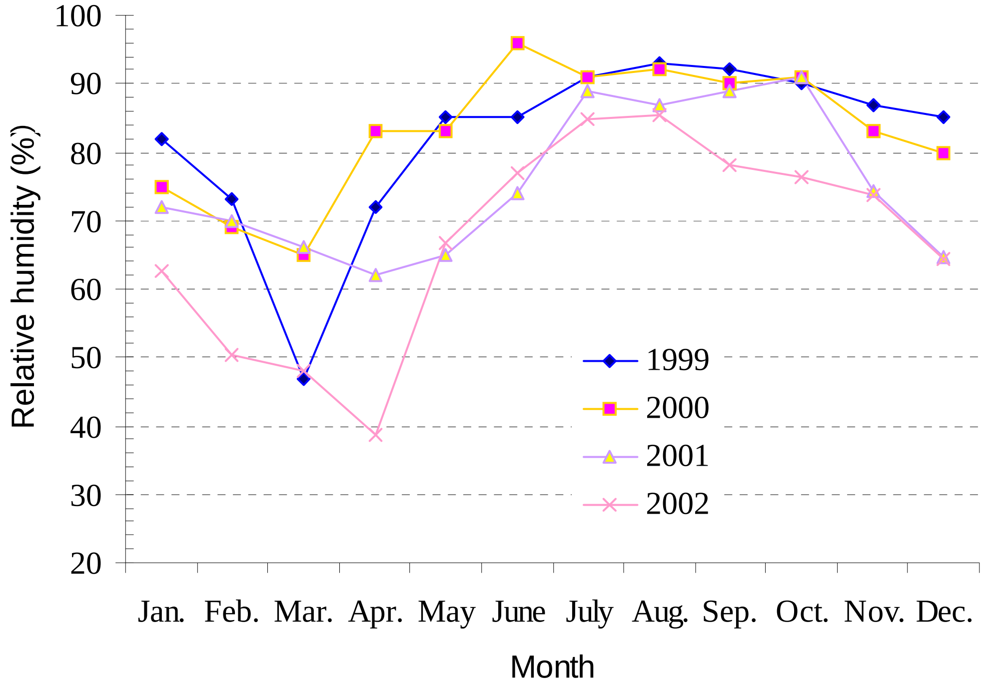
Figure 3.2.4. Monthly air temperature and soil temperature (°C) parameters in 2002.



Air relative humidity

Relative humidity data between 1999-2002 are summarized in Figure 3.2.5. There were different curves over the four years. The relative humidity of 2002 was generally lower than the other three years. In 2002, the air relative humidity in April was 39%, which was the lowest in four years. The highest humidity was observed in June 2000, at 96.0%. In general, during the dry season (November to April), relative humidity was low. The lowest humidity occurred in March or April, just before the rainy season started. During the rainy season (May to October), relative humidity was high in all years.

Figure 3.2.5. Monthly mean relative humidity during 1999-2002.

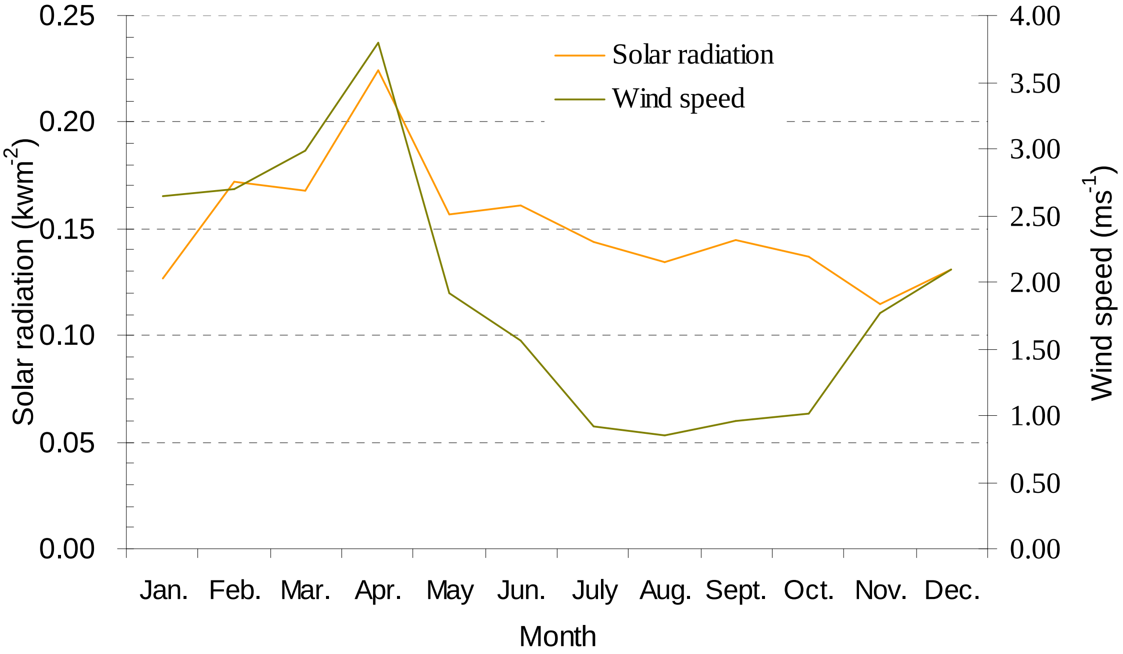


Solar radiation and wind speed

The highest monthly mean solar radiation was observed in April, before the rainy season started. At same time, wind speed was highest in the year (Figure 3.2.6). Solar radiation was not high during the summer time because of the cloud in the rainy season. Wind in the catchment was generally between 100-194° except in August, this means the wind came predominantly from southeast. In August, wind came normally from northeast, at 0-93°.

The combined effect of rainfall, humidity, radiation and wind made the winter and spring very dry in the catchment. Soil moisture content was so low that crops during this period of time were hardly able to survive without irrigation. This circumstance occurred with winter crops and sometimes in the early stage of summer crops, depending on different years.

Figure 3.2.6. Monthly mean solar radiation and wind velocity in 2002.



Variation in Wang Jia Catchment

The intra-catchment temperature variation can be considerable in Wang Jia Catchment. Generally, air temperature decreases 0.6-1.0°C with 100 m increase in elevation. In winter when it was dry, temperature differences could be 5.2°C (520 m × 1.0°C /100 m) between catchment foot and summit. During the rainy season in summer and autumn, temperature differences could be 3.1°C (520 m × 0.6°C /100 m). Even though the single temperature difference was not so great, the cumulative temperature for a crop growth season could be significantly different and greatly influence crop growth and variety selection. Provided maize growth duration is 120 days, the cumulative temperature difference would be 374.4°C (3.12°C/day ×120 days) which can have significant effects on maize growth (Walker, 1969). In addition, aspect influences soil temperature and moisture regimes.

3.2.1.2 Geology, lithology and mineralogy

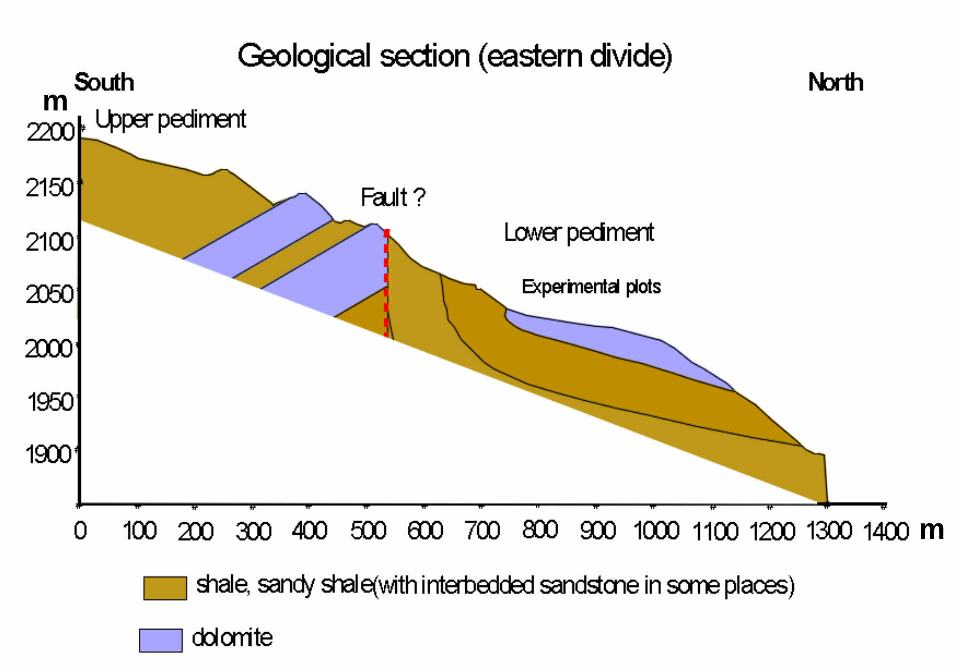
The nature of the parent material profoundly influences soil characteristics. A soil might inherit a sandy texture from a coarse-grained, quartz-rich parent material, such as sandstone. Soil texture, in turn, helps control the percolation of water through the soil profile, thereby affecting the translocation of fine soil particles and plant nutrients. The chemical and mineralogical composition of parent materials also influences both chemical weathering and the nature of vegetation. The presence of limestone in parent material will delay the development of acidity that typically occurs in humid climates. In addition, plants growing in limestone materials produce leaf litter that is relatively high in calcium. Incorporation of the calcium-rich litter into the soil further delays the process of acidification and, in humid temperate areas, the process of soil development. Parent material also influences the quantity and type of clay minerals present in the soil profile. First, the parent material itself may contain varying amounts and types of clay minerals, perhaps from a previous weathering cycle. Second, the nature of the parent material greatly influences the kinds of clays that can develop as the soil evolves. In turn, the nature of clay minerals markedly affects pedogenesis.

Geology

According to the geological map at 1:4,000,000 scale (Chao, 1970) and a geological sketch (Dusar, 1991) adapted from an Atlas of China, the geological formations in Wang Jia Catchment belong to the Permian System (P) or to the so-called undifferentiated Permo-Carboniferous (CP) (Figure 2.3). These geological formations have been affected by the Indosinian orogenesis which caused the emergence of the major part of the Chinese platforms, later by the Yanshan tectonic phases during the Mesozoic Era and Eocene Epoch, and finally by the Himalayan orogenesis during the Tertiary, with a general uplift of Yunnan Province (Yang, 1986). During the Quaternary, the Qinghai-Tibet Plateau uplifted more than 3,000 m with an average uplift rate of 1 mm/year (Yang, 1986).

Interpretation of local tectonic features is difficult in such a small area as Wang Jia Catchment. Relations between geology, relief and soils were given priority in this research. The rocks outcropping in Wang Jia and adjacent catchments were observed. As a result, a geological section sketch was produced (Figure 3.2.7). This sketch was a scoping interpretation of the complicated tectonic features in the catchment. The fault between the northern and southern parts of Wang Jia was just an interpretation of major changes in beds strike and dip. In the northern part, beds were striking N25-30°W with a general westward dip (35°-90°). In the central part, south of the fault, the strike was approximately E-W and the dip was 15-20° south. In the southern part, structures were less clear.

Figure 3.2.7. Geological section sketch along eastern divide in Wang Jia Catchment.



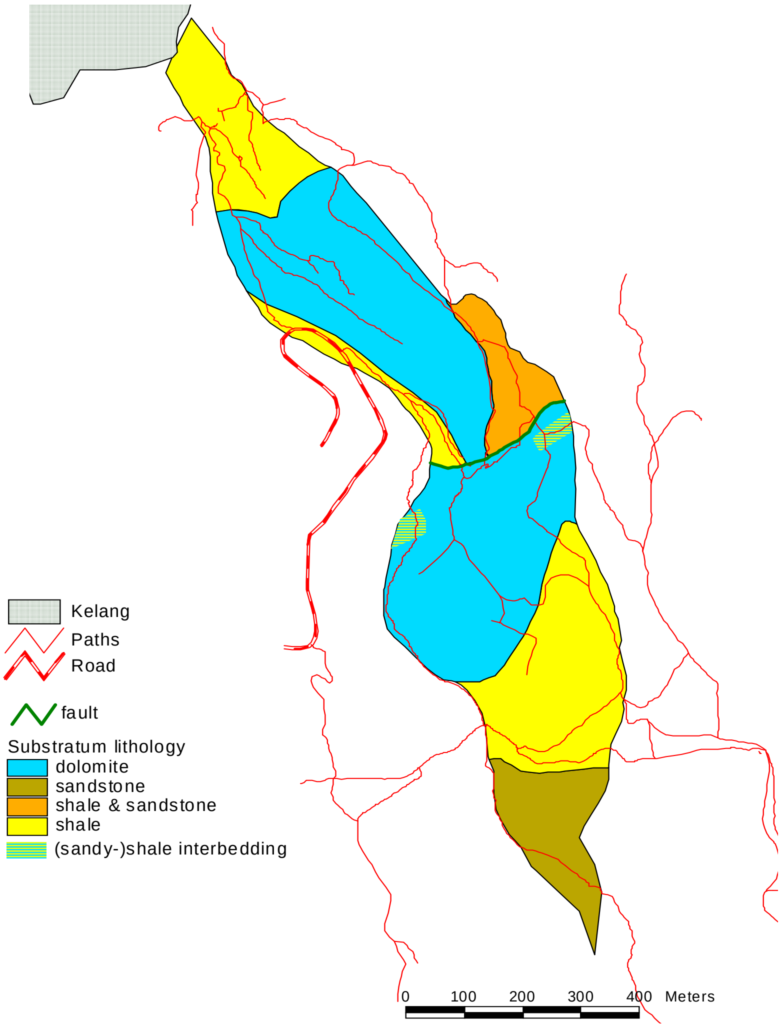
(Source: Bock and Lacroix, 2002)

Lithology

Three main lithologies have been identified: shale, sandstone and dolomite (or dolomitic limestone). The main rock types, their general setting and distribution in the catchment are shown in Figure 3.2.8. The catchment summit was dominated by sandstone, which constituted 6% of the catchment surface. Shale was observed in the foot and middle-upper part of the catchment (39%). Dolomite was distributed in the middle part of the catchment and occupied 55% of the catchment area. Where rocks were found the relevant outcrop was observed. In certain parts of the catchment, the lithology component was complicated. The most eastern area in the middle section had both shale and sandstone, and shale was occasionally interbedded in dolomite.

The sandstone is a feldspathic orthoquartzite, i.e. a feldspathic sandstone with a quartz cement. Detrital particles are, in decreasing order of frequency, quartz, K-feldspar, chalcedony and mica. The shale and sandy shale are laminated, yellowish or grey in colour and are locally interbedded with thin beds of sandstone. Besides the bedding plane, several planes due to tectonic stress were observed. One of the main shale mineralogical characteristics is high mica content. Dolomitic limestone and dolomite have a massive aspect, are thickly bedded and cut by a network of widely-spaced fractures. A conglomerate facies was locally observed. Under the microscope the rock showed a (dolo)sparitic or a micro(dolo)sparitic fabric; rather large crystals forming the bulk of the rock or being scattered in a fine matrix of micritic calcite and/or dolomite. Detrital quartz and mica were generally present in minor amounts.

Figure 3.2.8. Lithological sketch of Wang Jia Catchment.



(Source: Bock and Lacroix, 2002)

Mineralogy

The bulk and clay mineralogy of 52 soil samples collected from 19 soil profiles (soil sample set 1) were studied largely by X-ray diffraction (XRD). This set of soil samples was collected from different landscape units associated with changes of slope and diverse lithologies (Figure 2.5). The result is presented in Table 3.2.3.

In general, soil bulk mineralogy was dominated by quartz (65.8%), with subsidiary amounts of K-feldspar (9.0%) and small amounts of plagioclase feldspar. Data presented in parentheses are the mean of total samples. The other major components

Table 3.2.3 Catchment mineralogy, adapted from Baire and Ghuisoland (2001).

Location	Dominant lithology	Sample No.	Depth (cm)	Bulk soil mineralogy %											Clay mineralogy %				
				Quartz	Feldspar		Calcite	Dolomite	Illite	Chlorite	Smectite	Kaolinite	Hematite	Gibbsite	Illite	Chlorite	Smectite	Kaolinite	Gibbsite
					Plag	K													
Summit	Sandstone - shale	L 1.3.1	0 - 10	79,9	0,1	7,2			9,6	1,1		1,1	0,9		42,1	56,5		1,4	Trace
		L 1.3.2	I0 - 30	71,2	0,3	8,1			17,9			2,5			61,9	37,4		0,7	Trace
		L 1.3.3	30 - 120	62,5	1,5	7,5			27,1	0,7		0,7			52,9	47,2			
Upper part	Shale	L 2.3.1	0 - 20	73,1		15,4	0,3	1,8	8,2	1,0			0,4		74,5	24,1		1,4	Trace
		L 2.3.2	20 - 45	66,7		17,6	0,3	1,9	12,4	0,8			0,3		64,5	34,5			Medium
		L 2.3.3	45 - 90	72,1		16,1	0,3	1,9	8,6	0,7			0,4		88,5	11,5			
		L 2.3.4	90 - 120	67,4		22,2	0,3	2,0	6,2	1,9					79,6	20,4			
	Shale	L 1.6.1	0 - 10	80,9	0,9	6,8			7,1	2,0		1,8	0,5		64,9	33,4	1,7		
		L 1.6.2	I0 - 50	77,0	0,7	5,8		0,7	12,4	3,1			0,3		62,0	38,0			
		L 1.6.3	50 - 120	67,5	0,4	13,6		1,4	17,0						62,4	37,6			
	Dolomite	L 1.10.1	0 - 15	78,5	0,3	9,2			11,3	0,1			0,4		87,6	12,5			
		L 1.10.2	15 - 55	72,0	0,1	9,5			17,3	0,4		0,4	0,4		86,6	13,4			
	Dolomite	L 1.13.1	0 - 20	74,8	0,3	13,2			10,9	0,8					72,8	27,3			
		L 1.13.2	20 - 35	76,5	0,3	13,8			6,8	2,3			0,4		66,5	33,5			
		L 1.13.3	35 - 50	66,9	0,5	8,0			22,6	2,0					56,6	43,4			
		L 1.13.4	50 - 120	62,9	0,6	6,9		0,3	27,0	1,9					66,4	33,6			
	Shale	T 1.6.1	0 - 45	82,8		10,8			7,9	1,2					8,3	90,7		1,0	
		T 1.6.2	45 - 70	79,2		13,2		1,2	11,3	0,3			0,3		18,6	81,4			Trace
		T 1.6.3	70 - 120	78,9		11,4			15,8	1,3			0,4		61,4	38,6			
	Dolomite	T 1.7.1	0 - 15	54,3		9,1			27,5	1,9			7,2		29,9	68,5		1,6	
		T 1.7.2	15 - 60	47,0	1,1	3,3			28,4	3,8			16,4		34,6	65,0		0,4	Trace
	Dolomite	WP 2.1	0 - 25	76,3		11,1	0,5		12,0						73,8	24,9		1,3	
		WP 2.2	25 - 80	45,2	0,2	15,2			34,0	0,6		1,6	3,2		63,7	35,7		0,6	
		WP 2.3	80 - 150	29,5	0,4	14,0	0,4		44,0	0,4		6,6	3,7		65,3	34,7			
Middle part	Sandstone - shale	WP 3.1	0 - 10	83,1	0,1	10,6			5,0	1,1					33,5	66,5			Trace
		WP 3.2	I0 - 55	79,2	0,1	7,9	0,3		11,0	0,3		0,3	0,7	Trace	28,1	70,7		1,3	Trace
		WP 3.3	55 - 80	57,3	0,8	1,5		0,7	31,0	2,5			5,4		68,6	28,4		3,0	
		WP 3.4	80 - 170	62,1	0,6	1,5			22,0	2,6		9,5	2,2		81,3	14,2		4,6	
	Sandstone - shale	L 2.14.1	0 - 10	79,7		2,0			16,3	1,7			0,3		67,1	23,8		9,1	
		L 2.14.2	I0 - 35	79,5		0,6	0,1		19,1	0,4			0,2		77,5	17,3		5,2	
	Dolomite	T 2.5.1	0 - 15	27,8	1,1	3,2	0,1	58,2	6,2	1,2			2,2		25,2	70,3		4,5	Medium
	Dolomite	T 2.6.1	0 - 15	85,6		7,0		1,0	4,0	0,9			1,3	Trace	22,5	73,1		4,1	High
		T 2.6.2	15 - 70	82,0		7,6	0,5	0,3	7,6	0,9			1,0		28,4	67,0		4,6	High
		T 2.6.3	70 - 120	57,4	0,5	8,4	0,3	0,2	21,1	3,0			7,8	Trace	31,8	66,1		2,1	Medium
	Sandstone - Dolomite	L 2.20.1	0 - 35	82,7		6,4			7,9	0,7			2,3	Trace	34,6	49,0		16,6	High
		L 2.20.2	35 - 80	82,6		3,9			11,3	0,5			1,6	Trace	37,1	38,1		24,9	High
		L 2.20.3	80 - 120	70,3		8,4			15,8	1,3			3,2	Trace	85,1	8,9		6,0	Medium
	Dolomite	L 1.14.1	0 - 20	66,3	0,3	10,3	0,4	6,7	13,6	1,9			0,4		66,3	33,7			
		L 1.14.2	20 - 35	65,8	0,1	9,1	1,0	5,7	17,7	0,4			0,3		67,6	32,4			Trace
		L 1.14.3	35 - 60	65,6	0,4	8,1	1,6	6,2	17,3	0,6			0,3		65,7	34,4			Trace
		L 1.14.4	60 - 120	63,7	0,7	11,4	2,0	3,8	15,6	2,8					34,4	64,5		1,2	Medium
	Dolomite	L 1.17.1	0 - 15	59,1	0,4	6,4		3,6	27,3	1,1			2,1		38,0	62,0			Medium
		L 1.17.2	15 - 65	68,8	0,9	10,5		2,8	14,5	1,3			1,3		44,6	51,8		3,6	Medium
		L 1.17.3	65 - 120	66,5	0,9	8,9	0,5	6,4	13,8	0,5			2,3		65,2	31,2		3,6	Trace
	Shale	WP 1.1	0 - 10	48,1		1,0	0,4		6,0	1,9	38,6	0,4	2,3		13,4	54,1	14,5		
		WP 1.2	I0 - 80	21,9	0,3	3,3				5,2	60,8	6,7	1,8	Trace	13,2	33,2	50,0	3,6	
		WP 1.3	80 - 150	29,3		3,1			7,0	6,7	43,6		8,1		6,6	9,5	79,6	4,2	
		WP 1.4	150 - 190	40,5	0,7	9,0			2,0	7,1	36,6	1,0	3,4	Trace	8,5	9,7	78,5	3,3	
Lower part	Shale	L 1.26.1	0 - 20	56,0	0,3	13,1	0,3	3,2	26,5	0,5			0,2		76,7	19,0		4,3	Trace
		L 1.26.2	20 - 45	55,0	0,7	13,9	0,1	3,1	25,1	1,5			0,7		76,4	23,6			Trace
	Shale	L 1.27.1	0 - 15	73,5	0,2	10,5	2,0	8,0	5,8						70,5	27,8		1,7	Medium
		L 1.27.2	15 - 40	67,2	0,4	11,6	1,0	7,2	9,6	1,6			0,4		63,5	35,0		1,6	Medium

found included illite (15.4%) and chlorite (1.6%). There were important contributions of carbonate minerals, principally dolomite, where the parent material consisted of limestone. The main iron oxide mineral was haematite. In one profile (WP1), major amounts of smectite were detected but, as this is the only soil where this mineral was found, it may have derived from an external source connected with the construction of the water reservoirs.

Analysis of the clay fraction broadly confirmed the findings of the analysis of the bulk soils with respect to the clay mineralogy. The two major clay minerals found were illite (6.6-88.5%) and chlorite (8.9-90.7%), with minor kaolinite (0.4-24.9%). Profiles T2.6 and L 2.20 have medium to high gibbsite and WP1 was strongly smectitic.

The results suggest that the soils were still strongly influenced by their geological parent material and this impression was further reinforced by an examination of the mineralogy of the sand fractions of seven of the catchment soils by optical microscopy and by XRD studies of the fine fractions separated from selected rocks. Optical microscopy confirmed the presence of free carbonate minerals in the soils, in addition to other weatherable primary minerals, such as biotite and chlorite. XRD studies of the <2 μm fraction of some parent rocks showed a predominance of chlorite and mica, as well as an absence of kaolinite, exactly reflecting the major clay mineralogy found in the catchment soils (Wilson, 2002).

3.2.1.3 Morphological characterization

Topography is another primary factor in soil genesis and dynamics. Topography affects the abundance of solar energy in a given landscape, and in turn, interacts with vegetation to influence soil formation. Topography can interact with parent material as well. In many landscapes, topography reflects the distribution of residual, colluvial, and alluvial parent materials, with the residual materials on the upper slopes, colluvium covering the lower slopes and alluvium filling the valley bottom.

Landforms

Wang Jia Catchment has a SSE-NNW orientation. It is 200-345 m wide and 1930 m long with a relative relief of 520 m. There are clear influences of lithology and geostructures on catchment width and orientation. The widest zones are in shale areas

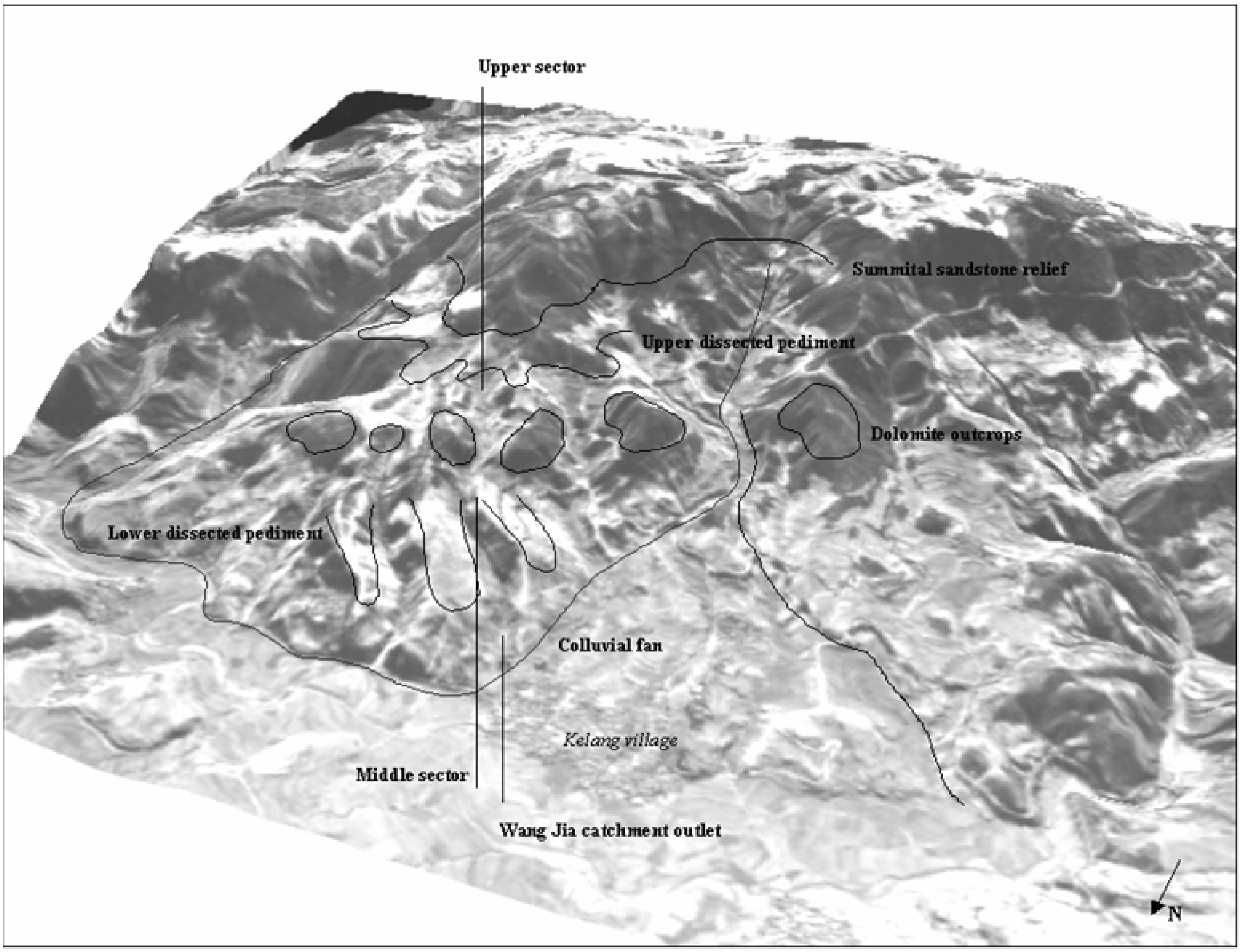
and the stream is parallel to the beds strike direction in the middle part. The physiographic feature of the catchment is shown in Figure 3.2.9 and Plate 3.2.1. Based on this figure and field observation, the catchment consisted primarily of three escarpments, two pediments and three different catchment floor morphologies and then divided physiographically into the following four sectors:

1. The Summital Relief (SR) stretches from 2,470-2,200 m in elevation, consists of steep rectilinear slopes (20-70%) and derives from sandstone (-shale) lithology.
2. The Upper Sector (US) stretches from 2,200-2,070 m and consists of predominantly upper dissected pediment. The eastern branch is relatively gentle due to shale material. The western branch has many dolomite outcrops.
3. The Middle Sector (MS) has an altitude of 2,070-1,940 m, which is predominantly made of lower pediment incised by a straight narrow stream passing through dolomite outcrop. Its eastern residual surface was the main cultivation area with red soils.
4. The Lower Sector (LS) has an altitude of 1,940-1,860 m, composed of the shale nose slope and outlet plain.

Slope

The slope units were determined by photo-interpretation (at the scale 1: 50,000) and field observations. According to the interfluve profile, the catchment eastern interfluve was divided into five parts (Figure 3.2.10). From upper (south) to lower (north), there were a steep mountain side, a low gradient erosion surface or upper pediment (8°), a short steeper slope (25°), a second erosion surface or lower pediment (5°) and nose slopes (20°), successively. The lower pediment is wider and more regular than other upslope segments, which are narrow convex ridges. Nose slopes are characterized by a broad irregular surface, slightly eroded by small streams with a steep longitudinal slope (20°).

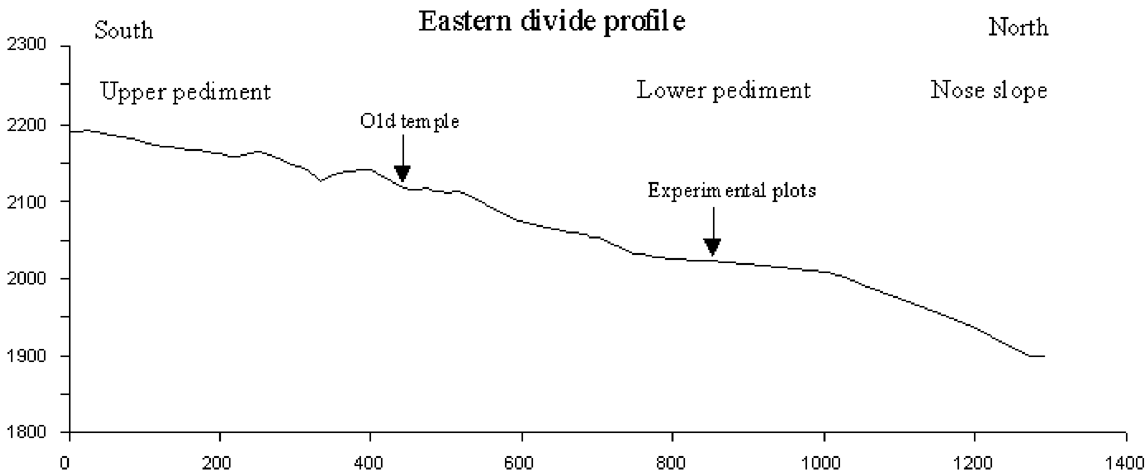
Figure 3.2.9. Three-dimensional oblique view of Wang Jia Catchment from the north-



west direction.

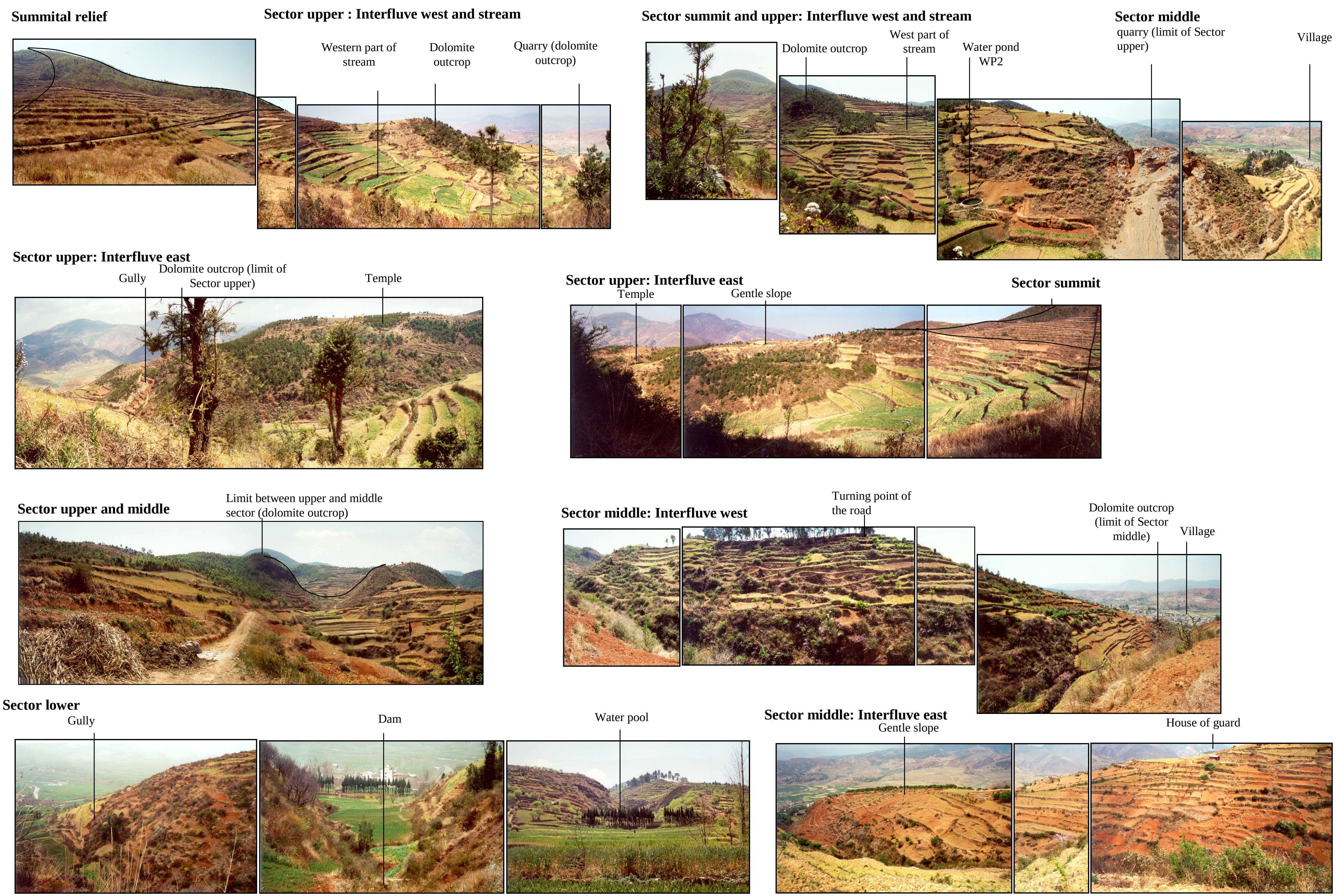
(Source: Vinck, 1999).

Figure 3.2.10. Eastern divided profile showing the different slope units.



(Source: Bock and Lacroix, 2002)

Plate 3.2.1. Catchment physiography, adapted from Baire and Ghuisoland (2001).



Further precise characterization of the catchment slope units is shown in Figure 3.2.11:

1. Catchment head (SR), closed by a north facing linear-linear mountain side (slope unit 1), can be divided into two parts, the smaller western one "hanging" above the main eastern one. The former can be described as a linear-concave slope (slope unit 3) and the latter as a concave slope (slope unit 2). These two parts are separated by a small dolomitic escarpment fading downward into a linear-convex slope (slope unit 4).
2. Catchment sides (US and MS) are generally characterized by rather steep (≤30-35°) linear-linear or convex - linear backslopes (slope units 5 and 6). In relation with the lower pediment surface, a convex-linear shoulder has developed (slope unit 9). Another shoulder ending into a small shelf is responsible for valley narrowing (slope unit 7).
3. Toe slopes (LS) on colluvial or alluvial bottom deposits (slope units 10,11,12) have a very limited extension due to the vertical erosion. In the catchment outlet the toe slope corresponds to a small fan apex (slope unit 13).

Morphometry (Figure 3.1.2)

<u>Linear variables</u>

Lt : streams length : 2,100 m

Lb : basin length : 1,930 m

P : basin perimeter : 4,290 m

<u>Areal variables</u>

A : basin area : 401,270 m^2

D : drainage density : Lt / A : 0.0052

Rc : circularity ratio : A / Ac : 0.279

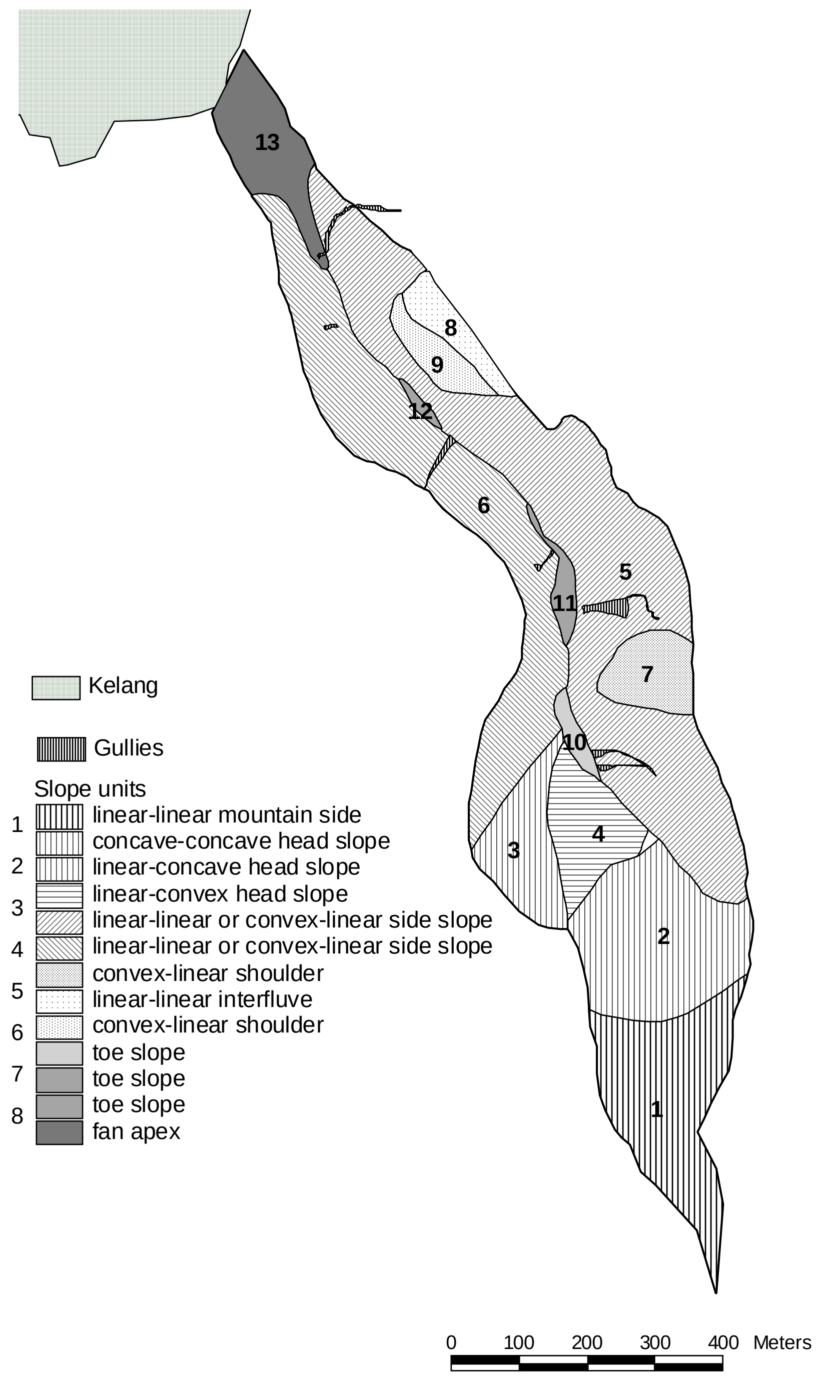
(Ac = area of circle having same perimeter P)

Re : elongation ratio : dc / Lb : 0.370

(dc = diameter of circle having same area A)

We : width of equivalent rectangle : 210 m

Figure 3.2.11. The sketch map of slope units in Wang Jia Catchment.

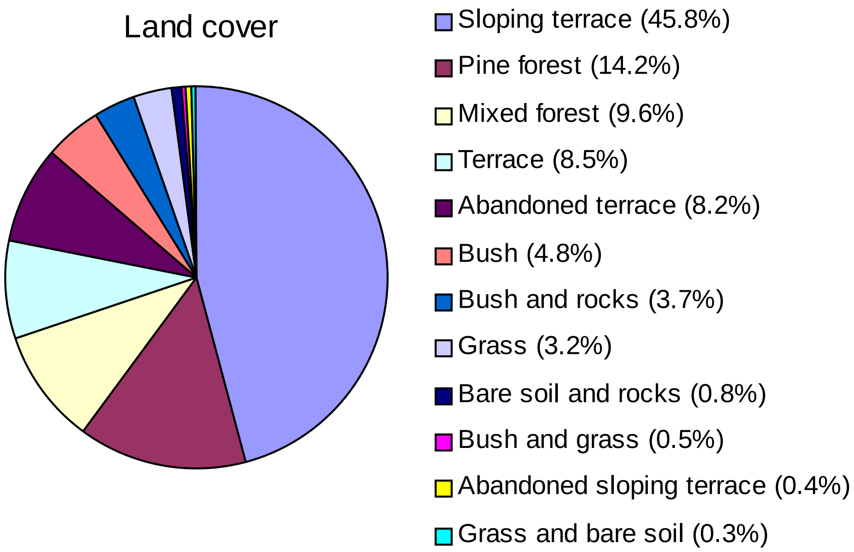


(Source: Bock and Lacroix, 2002)

3.2.1.4 Land cover

In the catchment, most areas are cultivated (54.3%). Only pieces of land where slopes are very steep or rocky and the head of the catchment where the temperature is not sufficiently high for selected crops are uncultivated (Figure 3.2.12). Therefore, it is difficult to describe the catchment in terms of natural vegetation and biodiversity. A preliminary qualitative vegetation survey was conducted with Mr. Li Rongchun, a botanist in YAU. The survey started from the foot of the catchment, observations were carried out along a path in the east division to the top of the catchment. The following shrubs, grasses and trees were recorded, including some cultivated plants.

Figure 3.2.12. Land cover in Wang Jia Catchment (12/04/01).



List of plants identified in Wang Jia Catchment

Rhamnella leptophyllus Schneid

Viburnum sp.

Pistacia weinmannifolia J. Poisson ex Franch

Eupatorium coelestinum L.

Rubus triphyllus Thunb.

Artemisia apiacea Hance

Chenopodium bonariensis (L) Cronq.

Berberis crispa Benth

Berberis wangji Schneid

Clematis chinensis Osbeck

Smilax sp.

Prinsepia untilis Royle

Euonymus sp.

Oenothera rosea Ait.

Gnaphalium affine D. Don

Hypericum acmosepalum

Myrsine africana L.

Setaria plicata (Lam.) T. Cooke

Rubia cordifolia. L.

Oenanthe javanica (Bl.) DC

Geranium nepalense Sweet

Artemisia annua L.

Duchesnea indica (Andre) Focke

Polygonum multiforum Thunb.

Solanum indicum. L.

Cotoneaster sp.

Cupressus torubsa. D. Don

Clematis florida Thunb.

Catharanthus sp.

Pyrus pashia Buch. –Ham. ex D. Don

Quercus acutissima Garr.

Capylotropis sp.

Celtis Yunnanensis Schneid

Cotoneaster microphyllus Wall. ex Lindl.

Carex baccans Nees

Rosa multiflora var. cathayensis Rehd. et Wils

Morus alba L.

Polygonum sp.

Senecio oxyzetorum Diels

Quercus variabilis Bl.

Castanea mollissima Bl.

Polygonum nepalense Meisn.

Litocarpus dealbatus

Cyclobalanopsis glauca Oerst.

Lyonia ovalifolia (Wall) Drude

Rhododendron spinuliferum Franch

Lotus corniculatus L.

Coriaria sinica Maxim

Cunninghamia lanceolata (Lam.) Hook.

Dichotomanthes tristaniaecarpa Kurz

Medicago sp.

Imperata cylindrica (L.) Beauv. v*ar. major* (Nees) C.E. Hubb.

Debregeasia sp.

Erianthus rufipilus (Steud) Griseb

Ficus ti-koua Bur.

Keteleeria evelynina Mast

Arundinella bengalensis (Spreng) Druce

Eragrostis sp.

Verbena officinalis L.

Setaria sp.

Bidens pilosa L.

Sanguisorba martini Lel.

Elaeagnus multiflora Thunb.

Rhododendron speciferum Franch

Scutellaria a. var. cenerea Hand-Mazz

Elsholtzia rugulosa Hemsl.

Myrica nana Cheval

Leontopodium sp.

Alnus nepalensis D. Don

Pinus armandii Franch

Gentiana sp.

Pinus yunnanensis Franch

Cirsium chlorolepsis Petrak

Scutellaria anoena H. Wright

Vaccinium fragile Franch

Zanthoxylum bungeanum Maxim

Fragaria chiloensis Duchesne

Gentiana sarcorrhiza Ling et Ma

Shuteria sp.

Toxicodendron delavayi Franch

Eucalyptus globulus Labill.

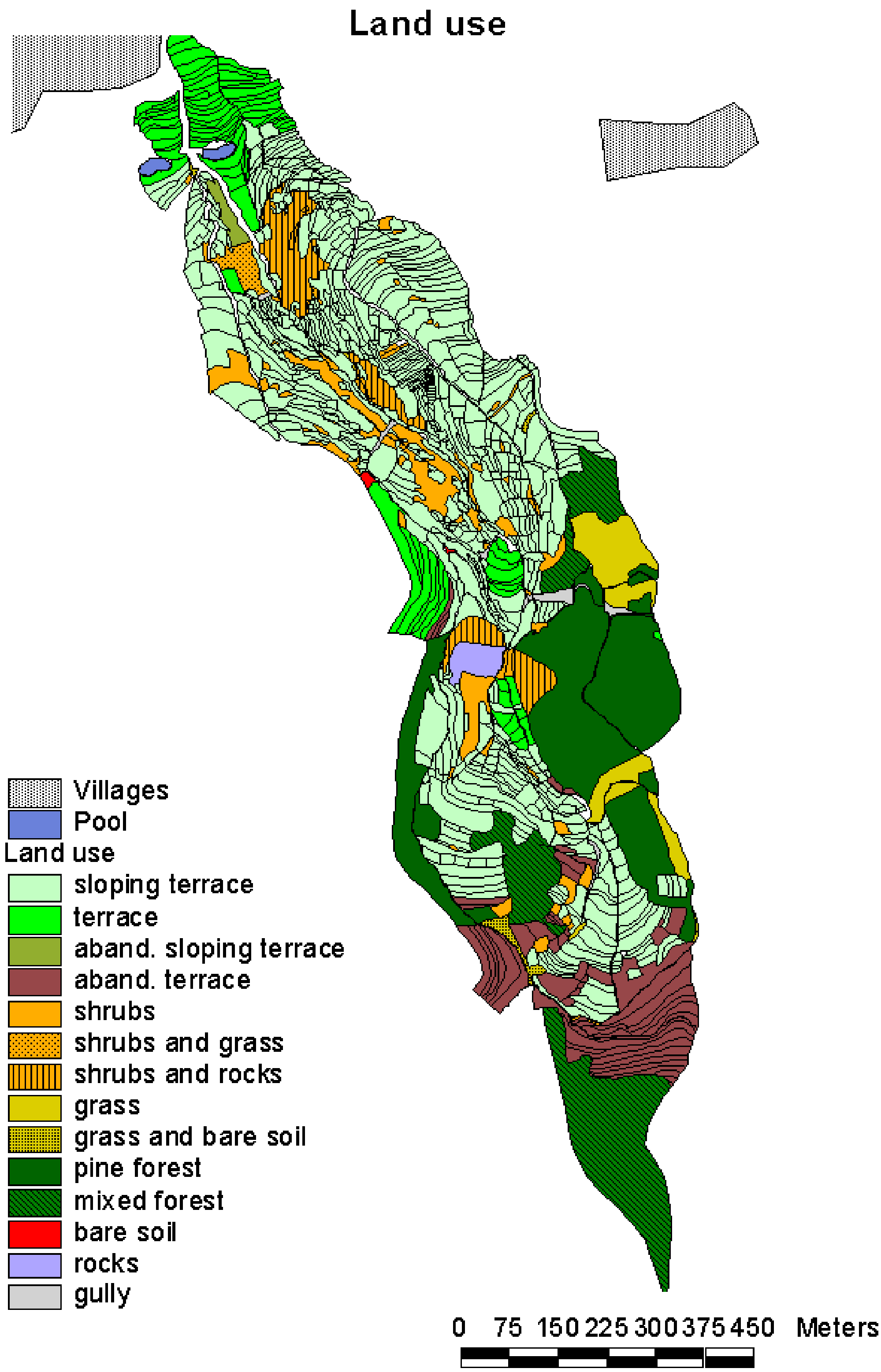
Natural vegetation influences soil properties in many ways, such as organic matter accumulation, biochemical weathering and nutrient cycling. The ability of natural vegetation to take up mineral elements strongly influences the characteristics of the soils that develop, especially their acidity. Soil acidity is more strongly developed under most coniferous vegetation than under most deciduous trees. Litter falling from coniferous trees (e.g., pines and firs) will recycle only small quantities of calcium, magnesium and potassium compared to those recycled by litter from some deciduous trees. In the middle and upper Wang Jia Catchment, several pieces of pine woodlands exist, the main pines being *Pinus yunnanensis* Franch and *Pinus armandii* Franch. While the main deciduous tree in mixed woodlands is *Alnus nepalensis* D.Don.

Plants evolved from different environments have different habits, tolerance and resistance to various soil properties. Certain plants were used to portray soil information, especially soil reaction. In the middle and upper catchment, *Rhododendron speciferum* Franch. was observed, which is a calcifuge.

3.2.1.5. Land use

Where terracing has been practiced as an agronomic technology, the soil was levelled, soil horizons were mixed and subsoil exposed. Different crop cultivation and tillage methods will bring about different influences on soil properties. Following the land tenure change in China, most areas in Wang Jia Catchment, especially the middle and upper part, were put into cultivation during the late 1950s to early 1960s (the so-called “big leap forward”). Terracing was massively implemented during this period of time in the catchment (Figure 3.2.13). An important sign of this activity was the upper abandoned terraces. This terrace was abandoned soon after construction due to low temperatures for selected crop production. The abandoned sloping terrace in the west lower catchment was due to shading and steep slope. The other sloping terraces and terraces were cropland, which was the focus of the soil fertility study. These land parcels were cultivated by more than 100 households with various fertilization inputs and cultivation methods. In addition, some small pieces of steep sloping land were put into cultivation just before this study in 1998. Therefore, the cultivation history of land parcels is diverse and difficult to assess.

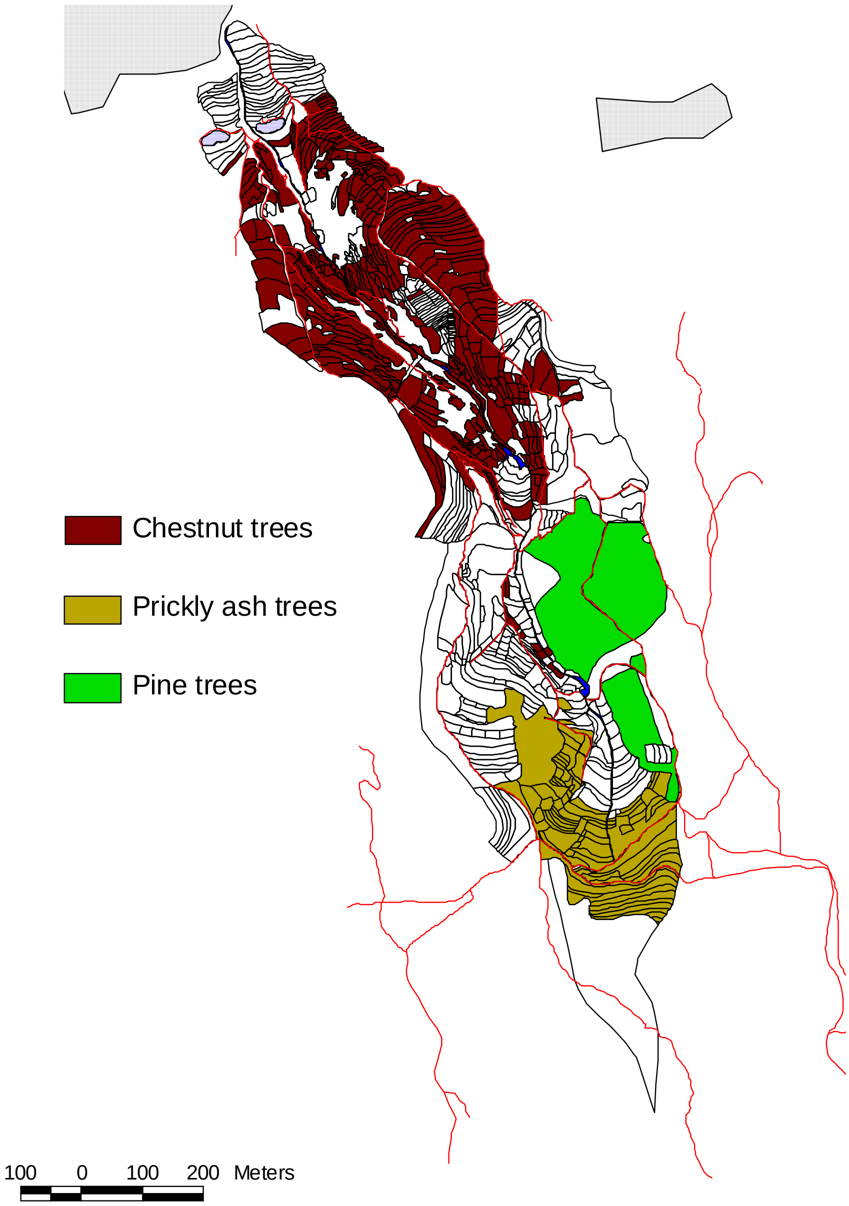
Figure 3.2.13. Land use in Wang Jia Catchment.



(Source: Bock and Lacroix, 2002)

As introduced in Section 1.6, several land uses were introduced in the catchment in this study, which included afforestation. A land use change map is shown in Figure 3.2.14. Some 40,000 Chinese pine (*Pinus armandii* Franch) seedlings were transplanted, the planting area occupied 15% of the catchment total area. Some 4,100 prickly ash (*Zanthoxylum bungeanum* Maxin) seedlings were transplanted in the upper catchment, where slopes are >25° and temperatures are too low for sweet chestnut trees. Over 15,000 sweet chestnut (*Castanea mollissima* Bl) seedlings were planted on the steeper slopes of the lower and middle catchment. The plantation areas of prickly ash and sweet chestnut covered >23 and 16% of the total catchment area, respectively. Crops were cultivated with these fruit-trees as agroforest system.

Figure 3.2.14. Layout of land use change in Wang Jia Catchment.



(Source: Bock and Lacroix, 2002)

3.2.2. Geomorphopedological identification

In order to express the information step by step, climate, geology, topography and vegetation were described separately in Section 3.2.1. In reality, these factors do not exert their influences independently. Indeed, interdependence is the norm. Soils are often defined in terms of these factors as *"dynamic natural bodies having properties derived from the combined effects of climate and biotic activities, as modified by topography, acting on parent materials over periods of time"* (Brady and Weil, 1999). The five factors influencing soil formation usually act simultaneously and interdependently. Thus, vegetation varies with climate and parent material may be related to topographic position, which may also influence vegetation. The interdependence of these factors presents a challenge to understand how a given soil was formed or predict what soil properties are likely to be encountered in a given environment. The climate, geology, topography and vegetation information of Wang Jia Catchment were used together to identify soil information in this section.

3.2.2.1. Four toposequences

The work involved in this section was mainly conducted by Vinck (1999) and adapted by Baire and Ghuisoland (2001). It is impractical to dig soil profiles all over the landscape to determine soil information. Instead, hand augering was used and based on the interplay of the soil forming factors in a landscape; the clues from geology, topography and vegetation were used to select four toposequences in Wang Jia Catchment.

The toposequence along the narrow alluvial plain

This toposequence was noted as L1 in Figure 2.5, which is a longitudinal transect along the narrow valley bed in the catchment. It started at the summit of the catchment and crossed diverse landscape units from the mixed forest at the summit to the cultivated sloping terrace and terrace in the upper, middle and lower parts (Figure 3.2.15). In total, 27 augerings were made and soil information described (Table 3.2.4), among which eight augerings were sampled for laboratory analysis (Table 3.2.5). Mineralogy data were presented in Table 3.2.3.

Figure 3.2.15. Biophysical sequence along the narrow alluvial plain in Wang Jia Catchment, from Vinck (1999) adapted by Baire and Ghuisoland (2001).

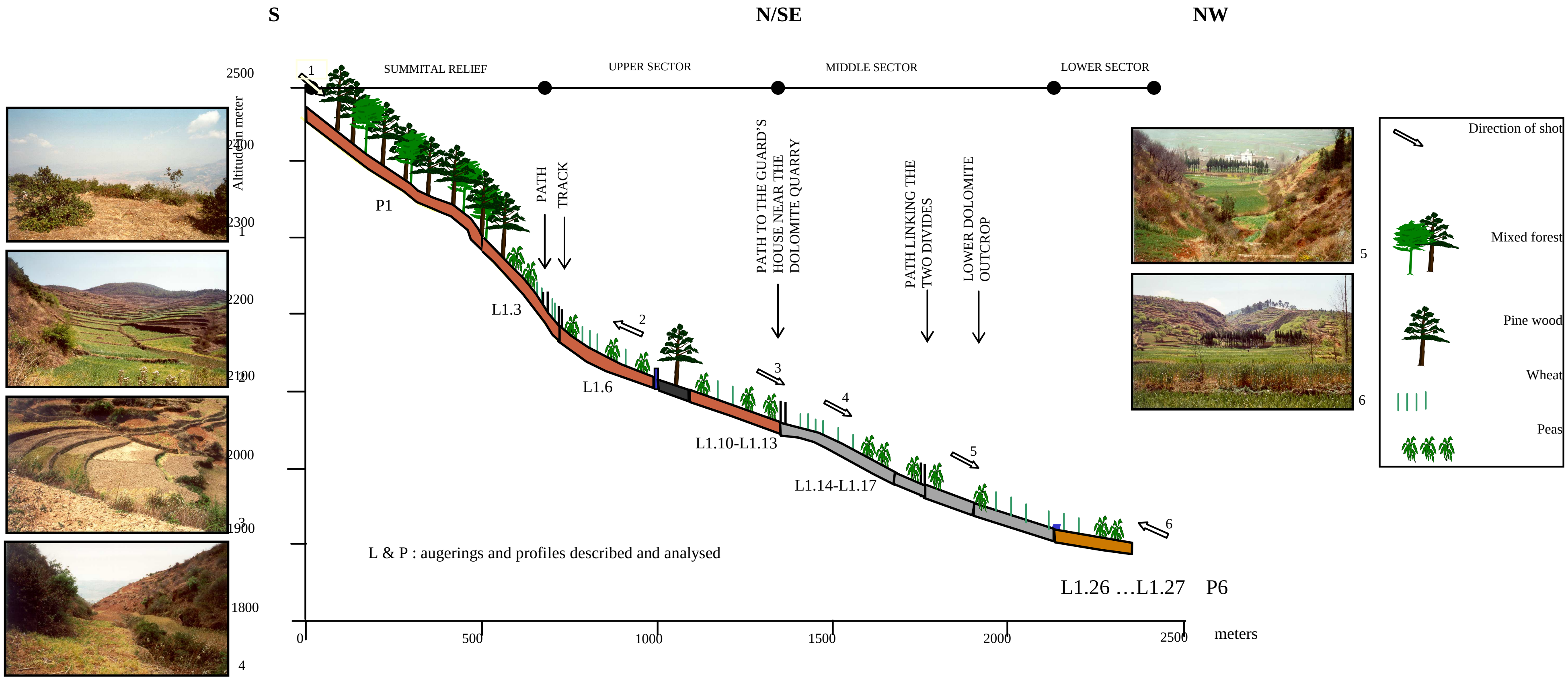


Table 3.2.4. The field description of the augerings along the narrow alluvial plain, adapted from Vinck (1999).

Location	Augering N°	Depth (cm)	Texture	Colour	Lithology of Stones*	pH
Summital relief	L1.1	10	Sand	7.5YR 5/6	sandstone	5
	L1.2	15	Sand	10YR 3/4	sandstone	4.5-5
		25	Sand	10YR 5/8	sandstone	4.5-5
		100	Sand	7.5YR 5/8	sandstone	4.5-5
	L1.3	10	Sandy loam	10YR4/6	sandstone	5
		30	Sandy loam	10YR7/8	sandstone/shale	5
		120	Sandy clay loam	10YR7/8	sandstone/shale	5
	L1.4	5	Sandy loam	10YR5/8	sandstone	5
		15	Sandy loam	10YR6/8	sandstone	5
		120	Sandy clay loam	10YR7/8		5
Upper part	L1.5	25	Sandy loam	10YR4/4	sandstone/shale	5.5-6
		120	Sandy clay loam	10YR4/6	sandstone/shale	5.5-6
	L1.6	10	Sandy loam	10YR4/4	sandstone	5.5-6
		50	Sandy loam	10YR4/6	sandstone	5.5-6
		120	Sandy clay loam	10YR2/3	sandstone	5.5-6
	L1.7	-	-	10YR4/4	shale	5
	L1.8	40	-	-	shale	-
	L1.9	30	Sandy loam	10YR4/4	shale/sandstone	5.5-6
		60	Sandy loam	10YR4/6	sandstone	5.5-6
		120	Sandy loam	10YR2/3	sandstone	5.5-6
	L1.10	15	Sandy loam	10YR6/6	shale/sandstone	6
		55	Sandy loam	10YR5/8	shale/sandstone	6
		80	Sandy clay loam	10YR4/6	sandstone	5.5
		120	Sandy clay loam	10YR2/3	sandstone	5.5
	L1.11	25	Sandy loam	10YR6/6	shale/sandstone	6
		50	Sandy loam	10YR5/8	shale/sandstone	6
		75	-	-	-	-
		120	Sandy clay loam	10YR3/4	sandstone	5.5
	L1.12	20	Sandy loam	10YR5/6	shale/sandstone	5
		50	Sandy loam	10YR4/6	shale/sandstone	6
		120	Sandy clay loam	10YR3/4	sandstone	6
	L.1.13	20	Sandy loam	7.5YR5/6	sandstone	6.5
		35	Sandy loam	7.5YR4/6	sandstone	6.5

Upper part	L1.13	50	Sandy loam	7.5YR3/4	sandstone	7
		120	Sandy clay loam	10YR3/4	sandstone	7
Middle part	L1.14	20	Sandy loam	7.5YR5/6	sandstone/dolomite	7
		35	Loam	7.5YR4/6	sandstone/dolomite	7
		60	Loam	7.5YR3/4	sandstone/dolomite	7
		120	Clay loam	7.5YR3/4	sandstone/dolomite	7
	L1.15	20	Sandy loam	10YR4/6	dolomite/sandstone	7
		35	Loam	10YR3/4	dolomite/sandstone	7
		110	Loam	10YR3/4	dolomite/sandstone	7
	L1.16	20	Sandy loam	10YR4/6	dolomite/sandstone	7
		25	Loam	10YR3/4	dolomite/sandstone	7
		100	Loam	10YR3/4	dolomite/sandstone	7
	L1.17	15	Loamy clay	5YR4/6	dolomite	7
		65	Loamy clay	5YR3/6	dolomite	7
		120	Loam	7.5YR3/4	dolomite/sandstone	6.5
	L1.18	15	Sandy loam	7.5YR4/6	dolomite/sandstone	6.5
		20	Sandy loam	7.5YR4/4	dolomite/sandstone	6.5
		120	Sandy loam	7.5YR3/4	dolomite/sandstone	6.5
	L1.19	15	Sandy loam	7.5YR4/4	dolomite/sandstone	6.5
		40	Sandy loam	10YR4/6	dolomite/sandstone	7
		85	Sandy loam	7.5YR3/4	dolomite/sandstone	7
		110	Sandy loam	7.5YR4/6	dolomite/sandstone	7
	L1.20	15	Sandy loam	7.5YR4/4	dolomite/sandstone	7
		40	Sandy loam	10YR4/6	dolomite/sandstone	7
		85	Sandy loam	7.5YR3/4	dolomite/sandstone	7
		110	Sandy loam	7.5YR4/6	dolomite/sandstone	7
	L1.21	15	Sandy loam	7.5YR4/4	dolomite/sandstone	7
		40	Sandy loam	10YR4/6	dolomite/sandstone	7
		85	Sandy loam	7.5YR3/4	dolomite/sandstone	7
		110	Sandy loam	7.5YR4/6	dolomite/sandstone	7
	L1.22	15	Loam	7.5YR4/6	dolomite	7
		35	Loam	5YR3/6	dolomite	7
		100	Sandy loam	7.5YR3/4	dolomite/sandstone	7
	L1.23	20	Loam	10YR4/6	shale	6.5
		40	Loam	10YR3/4	shale	6.5
		120	Clay loam	5YR2/4	shale/dolomite	7
	L.1.24	40	Loam	5YR 3/6	shale/dolomite	7

Middle part	L1.24	120	Clay loam	5YR3/6	dolomite	7
	L1.25	40	Clay loam	5YR3/6	dolomite	7
Lower part	L1.26	20	Loam	10YR6/4	shale/dolomite/sandstone	7
		45	Loam	10YR5/6	shale/dolomite/sandstone	7
	L1.27	15	Loam	10YR6/4	shale/dolomite/sandstone	7
		40	Loam	10YR5/6	shale/dolomite/sandstone	7

* Stoniness is normally <15%, except for L1.1, L1.19 to L1.21 at 40 and 85 cm, L1.24 at 120 cm and L1.26 at 20 cm, where the stoniness was 15-50%.

In summary, at the summital relief under the mixed forest or abandoned terraces, soil was mainly influenced by sandstone. Therefore, soil texture assessed by hand was relatively sandy. Soil stoniness was normally <15% of sandstone or a mixture of sandstone and shale. The soils were reddish brown and tended to be acidic through all the depths, with pH <6.0 and base saturation <65%. The subsoil had the lowest organic carbon content compared with the topsoil in this sequence. Clay mineralogy was dominated by a simple chlorite/illite assemblage, with little kaolinite and trace amounts of gibbsite. From the mineralogical data, it may be concluded that soils in the summit show little evidence of intensive weathering.

In the upper part, soils were mainly cultivated as sloping terraces and terraces. As developed from alluvial material, these soils started to become influenced by shale and dolomite locally or colluvium from further upslope and side slopes. The soil stoniness was normally <15% and consisted of mixtures of sandstone and shale or dolomite and sandstone. Soil texture was normally loam to sandy loam assessed by hand and silt loam by granulometer. Together with strong influences of human cultivation, soil pH increased from 5.4 over shale to 7.3 over dolomite. Soil base saturation was 65–100%, with CEC 6.1–18.6 me/100g. Topsoil normally had more total organic carbon than subsoil. The general content of organic matter was higher than at the summit, but less than middle and lower parts. Clay mineralogy was similar to the summit, showing little evidence of intensive weathering.

In the middle part, the plain becomes narrower and soils were mainly cultivated as terraces. The influence of dolomite became stronger. Soil stoniness was normally

Table 3.2.5. Laboratory analyses of the toposequence along the narrow alluvial plain, data adapted from Baire and Ghuisoland (2001).

Sector	Parent material	Land use	Augering	Depth (cm)	Granulometer				Acidity				Total organic matter			CEC		Exchangeable base at pH 7					Base saturation
					FAO Texture	%			pH		me/100g		%			me/100g		me/100g					%
						Clay	Silt	Sand	H_2O	$CaCl_2$	Exchangeable acidity	Exchangeable Al^{3+}	Total C	Total N	C/N	Tm	Teff	Ca	Mg	Na	K	Σ	V
Summit	Sandstone - shale	Abandoned terrace	L 1.3.1	0 - 10	Silt loam	15,79	71,5	12,71	5,6	5,0	4,7		1,4	0,11	12,5	13,6	11,7	4,85	1,77	0,02	0,26	6,90	50,6
			L 1.3.2	I0 - 30	Silt loam	12,77	78,0	9,25	5,5	4,8	2,1		0,3	0,04	6,5	10,2	8,4	4,06	2,01	0,01	0,17	6,25	61,5
			L 1.3.3	30 - 120	Silt loam	14,51	78,3	7,19	6,0	5,0	1,2		0,2	0,03	5,3	14,1	10,2	5,81	2,93	0,02	0,22	8,98	63,6
Upper	Shale	Cultivated sloping terrace	L 1.6.1	0 - 10	Silt loam	14,07	66,6	19,37	6,3	6,1			1,6	0,13	12,1	16,4	22,7	9,89	3,53	0,02	0,18	13,62	82,8
			L 1.6.2	I0 - 50	Silt loam	15,36	65,4	19,28	6,0	5,4	3,9		1,1	0,08	13,4	14,3	14,5	7,00	2,34	0,03	0,15	9,52	66,5
			L 1.6.3	50 - 120	Silt loam	18,03	69,6	12,37	5,9	5,5	4,9		2,2	0,12	18,6	19,2	20,7	11,98	3,61	0,03	0,17	15,79	82,2
	Dolomite	Cultivated sloping terrace	L 1.10.1	0 - 15	Silt loam	14,43	62,8	22,79	6,3	5,9	2,3		1,2	0,10	12,1	9,8	10,3	6,10	1,63	0,02	0,16	7,91	80,7
			L 1.10.2	15 - 55	Silt loam	14,77	66,5	18,78	6,7	6,3	0,8		0,9	0,08	11,5	9,6	8,8	6,15	1,75	<0.01	0,13	8,04	83,4
	Dolomite	Cultivated terrace	L 1.13.1	0 - 20	Silt loam	14,61	62,9	22,48	7,1	6,8	0,4		1,0	0,08	12,1	9,3	10,3	7,45	2,20	<0.01	0,20	9,86	
			L 1.13.2	20 - 35	Silt loam	15,88	66,6	17,56	6,7	6,3	0,7		0,5	0,08	6,5	9,8	9,8	6,86	2,03	0,04	0,15	9,08	92,7
			L 1.13.3	35 - 50	Silt loam	17,38	68,1	14,5	7,2	6,7			0,6	0,09	6,1	13,2	15,5	11,12	4,13	0,03	0,18	15,46	
			L 1.13.4	50 - 120	Silt loam	17,79	69,6	12,68	7,3	6,8			0,7	0,08	8,4	14,5	14,5	10,18	4,18	0,02	0,15	14,53	
Middle	Dolomite	Cultivated sloping terrace	L 1.14.1	0 - 20	Silt loam	14,53	63,7	21,81	7,5	7,4			1,8	0,17	10,4	16,7	22,9	18,94	3,59	0,02	0,29	22,84	
			L 1.14.2	20 - 35	Silt loam	14,53	60,6	24,91	7,7	7,5			1,2	0,12	9,9	11,8	27,1	23,62	3,15	0,02	0,18	26,97	
			L 1.14.3	35 - 60	Silt loam	16,62	69,0	14,41	7,7	7,5			1,4	0,14	9,6	13,2	31,1	27,25	3,62	0,02	0,17	31,06	
			L 1.14.4	60 - 120	Silty clay loam	16,68	75,0	8,34	7,5	7,5			1,2	0,14	8,6	19,0	31,8	27,34	4,24	0,02	0,17	31,77	
	Dolomite	Cultivated terrace	L 1.17.1	0 - 15	Silty clay loam	24,47	65,9	9,61	7,3	7,1			1,8	0,18	9,8	22,5	20,8	14,39	5,82	0,01	0,58	20,80	92,4
			L 1.17.2	15 - 65	Silty clay loam	26,77	65,0	8,23	7,4	7,2			1,7	0,18	9,6	27,2	21,4	15,16	5,79	0,03	0,39	21,37	78,7
			L 1.17.3	65 - 120	Silt loam	21,83	55,0	23,16	7,6	7,5			1,5	0,15	10,1	20,9	28,7	23,02	5,38	0,03	0,24	28,67	
Lower	Shale	Cultivated terrace	L 1.26.1	0 - 20	Loam	10,72	48,3	41,02	6,9	7,0			1,8	0,19	9,5	12,9	16,9	13,09	3,38	0,03	0,40	16,90	
			L 1.26.2	20 - 45	Silt loam	12,58	50,3	37,11	7,1	7,1			1,5	0,18	8,5	13,7	17,5	13,39	3,70	0,02	0,38	17,49	
	Shale	Cultivated terrace	L 1.27.1	0 - 15	Silt loam	19,48	65,4	15,1	7,5	7,7			1,6	0,17	9,4	16,8	32,5	28,45	3,86	0,04	0,19	32,54	
			L 1.27.2	15 - 40	Silt loam	20,14	65,7	14,21	7,4	7,7			1,5	0,17	8,6	15,7	30,5	26,50	3,75	0,03	0,19	30,47	

<15%, sometimes 15–50 %, and consisted of a mixture of dolomite and sandstone. Soil texture assessed by hand was normally loam to sandy loam, silt to silty clay loam by granulometer. Together with strong influence of cultivation, soil pH was generally ~7, with the highest 7.7, close to the dolomite outcrops. Soil base saturation was well saturated with CEC of 11.8–27.2 me/100g. The mean organic carbon content was as high as the lower part. These indicated relatively high soil potential fertility in this sector. The high organic carbon content at depth may have been due to the terracing or leaching of solutes through soil profiles in the karst landscape or both. Clay mineralogy was similar to the upper and summital relief, dominated by a simple chlorite/illite assemblage. But the kaolinite and gibbsite, even haematite in bulk mineralogy, were relatively higher than that of the upper and summital relief. This indicated relatively stronger weathering, although it was still not intensive.

In lower parts, soils were mainly cultivated as terraces for crops, including maize, wheat, tobacco and vegetables. The influence from humans became stronger. The local lithology was shale, but with strong influences from dolomite and sandstone from the higher position. Soil stoniness was normally <15% of the mixture of shale, dolomite and sandstone. Soil texture assessed by hand was normally loam, silt loam to loam by granulometer. Soil pH was ~7. Soil was well saturated, with CEC of 12.9–16.8 me/100g and the average organic carbon content was high. These indicated a relatively high soil fertility in this sector and the clay mineralogy was similar to the middle part.

The toposequence along the east interfluve

This toposequence was noted as L2 in Figure 2.5, which is a longitudinal transect across various landscape units along the eastern interfluve (Figure 3.2.16). This toposequence started at the pine forest in the upper part to the cultivated sloping terrace and terrace in the middle and lower part. In total, 23 augerings were made and soil information described (Table 3.2.6), among which three augerings were sampled for laboratory analysis (Table 3.2.7). Mineralogy data are shown in Table 3.2.3.

Table 3.2.6. The field description of the augerings along the east interfluve, adapted from Vinck (1999).

Location	Augering N°	Depth (cm)	Texture	Colour	Dominant lithology of stones	pH
Upper part	L2.1	20	Loam	10YR 6/4	Shale	5
		50	Loam	10YR 6/4	Shale	5
		120	Loam	10YR 6/6	Shale	5
	L2.2	10	Loam	10YR 6/4	Shale	5
		30	Loam	10YR 6/4	Shale	5
		80	Loam	10YR 6/6	Shale	5
	L2.3	20	Loam	10YR7/6	Shale	5
		45	Loam	10YR6/8	Shale	5
		90	Loam	10YR6/8	Shale	5
		120	Clay loam	10YR6/6	Shale	5
	L2.4	10	Loam	10YR7/4	Shale	5
		25	Loam	10YR6/6	Shale	5
		120	Loam	10YR6/6	Shale	4.5
	L2.5	10	Loam	10YR7/6	Shale	5
		30	Loam	10YR6/8	Shale	5
		110	Loam	10YR6/8	Shale	5
		120	Clay loam	10YR6/6	Shale	5
	L2.6	10	Loam	10YR6/6	Shale	4.5
		40	Clay loam	10YR6/8	Shale	4.5
	L2.7	15	Loam	10YR6/7	Shale	6
	L2.8	10	Clay loam	5YR 4/6	Dolomite	6
		80	Clay	2.5YR3/6	Dolomite	6
	L2.9	10	Clay loam	5YR 4/6	Dolomite	5
		80	Clay	2.5YR3/6	Dolomite	5
Middle part	L2.10	10	Loam	10YR8/4	Shale	5.5
		20	Loam	10YR7/4	Shale	5.5
		45	Loam	10YR6/6	Shale	5
		100	Loam	10YR6/8	Shale	5
	L2.11	30	Loam	10YR7/4	Shale	5
	L2.12	20	Loam	10YR7/4	Shale	4
	L2.13	10	Clay	7.5YR5/8	Dolomite/shale	4.5
		25	Clay	5YR5/8	Dolomite	4.5
		50	Clay	5YR3/6	Dolomite	4.5
		120	Clay	2.5YR3/6	Dolomite	4.5
Middle part	L2.14	10	Loam	7.5YR6/6	Sandstone/shale	5
		35	Sandy loam	5YR7/4	Sandstone/shale	5
	L2.15	10	Sandy loam	7.5YR5/6	Shale	5

		35	Sandy loam	7.5YR5/6	Shale	5
		50	Loam	7.5YR5/8	Shale	5
	L2.16	10	Sandy loam	7.5YR5/6	Shale	5
		25	Sandy loam	7.5YR5/6	Shale	5
		70	Loam	7.5YR5/8	Sandstone/shale	5
	L2.17	10	Sandy loam	7.5YR4/6	Shale	5
		35	Sandy loam	7.5YR4/6	Shale	5
		100	Loam	7.5YR5/8	Shale	7
	L2.18	10	Sandy loam	7.5YR4/6	Shale	7
		35	Loam	7.5YR4/6	Shale	7
		100	Loam	7.5YR5/8	Shale	7
	L2.19	25	Sandy loam	7.5YR5/8	Shale	7
		45	Loam	7.5YR5/8	Shale	7
		120	Loam	7.5YR5/8	Shale	7
	L2.20	35	Loam	7.5YR5/8	Shale/dolomite	5
		80	Loam	5YR3/6	Dolomite	5
		120	Clay loam	5YR3/6	Dolomite	5
	L2.21	40	Clay loam	5YR3/6	Shale/sandstone/dolomite	5
Lower part	L2.22	20	Sandy loam	10YR6/8	Shale/sandstone/dolomite	5.5
	L2.23	20	Sandy loam	7.5YR5/6	Shale/sandstone/dolomite	5.5

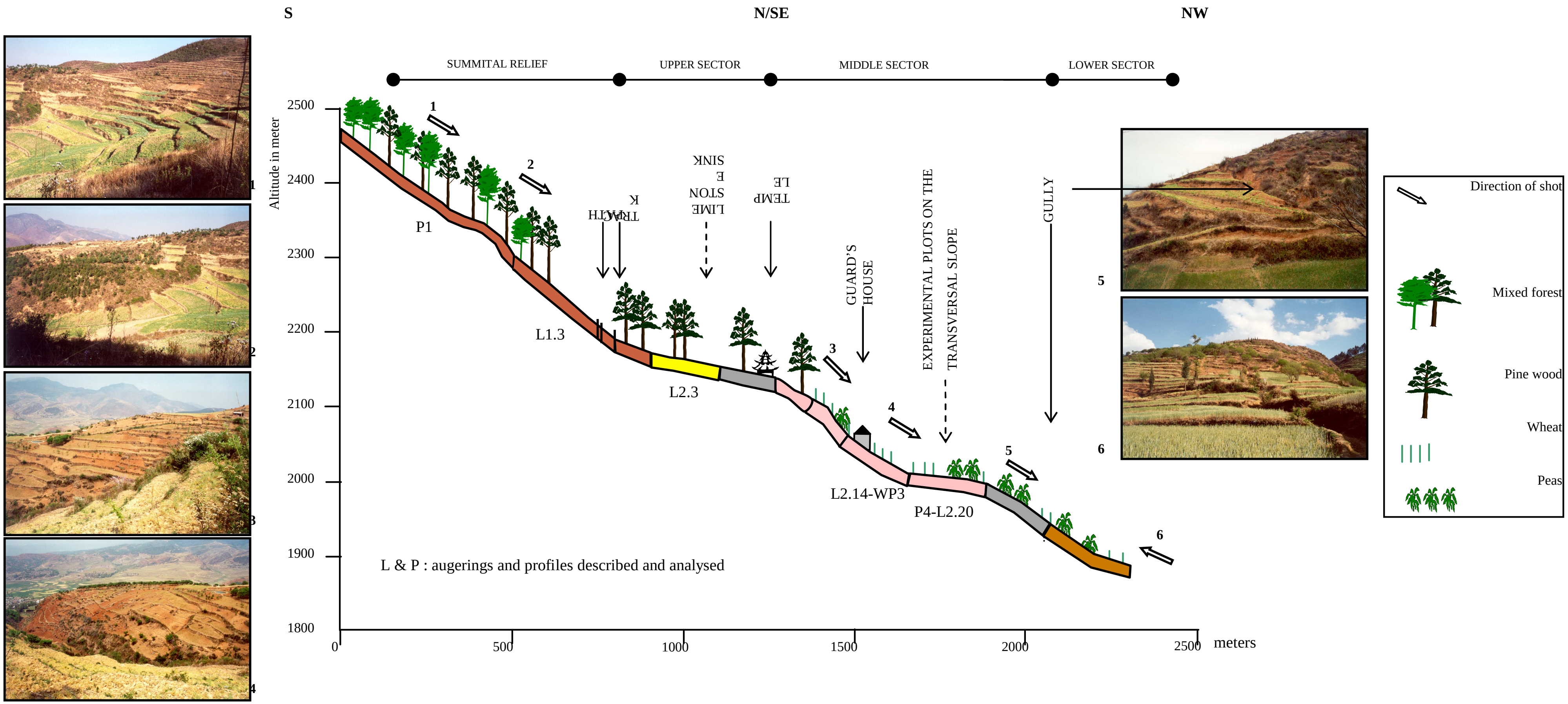
Note: Stoniness was normally <15%, except for L2.7, L2.10 at 20 cm, L2.15 at 10 cm, L2.16 at 10 and 100 cm, L2.17 and L2.18 at 10 cm, and L2.22 and L2.23 at 20 cm, where the stoniness was 15-50%. The abundance of stoniness for L2.10 at 10 cm was >50%.

In brief, soils in the upper part of the eastern interfluve were purely under pine trees with occasional large patches of bare soil. The pine tree plantation was mainly implemented at this part, especially close to the divide where the forest was very sparse, on shale outcrops close to the summit and dolomite outcrops close to the middle part. However, where the bare soil was exposed with shale outcrops, the survival rate of pine trees was very low, probably because the topsoil was truncated by erosion and the exposed subsoils were very hard. Due to the differences in resistance to erosion, the soils developed from shale were generally more gently-sloping than the soils developed from dolomite. The soil stoniness was normally <15% of shale or dolomite. Soil texture by hand assessment was normally loam to clay loam down to the dolomite outcrop, silt loam by granulometer analysis. Soils were acidic throughout, with pH <6.0, even over dolomite, which may be due to interbedding of shale. The only augered profile analysed in the laboratory (L2.3) showed a base saturation of 41.4% at the top and increased to 70.5% at 90-120 cm, with CEC of 5.7-8.5 me/100g, showing a very small buffer capacity and cation holding capacity and thus low inherent soil fertility. Clay mineralogy was dominated by a simple chlorite/illite assemblage, with illite dominant. Small amounts of kaolinite and gibbsite were found. The K-Feldspar content in bulk mineralogy was the highest one among all the augered samples. Dolomite and calcite were found in the bulk mineralogy. Soil organic carbon normally was very low, especially compared to the alluvial plain.

In the middle part, land cover started with pine forest and then cultivated sloping terraces. The lithology was dominated by dolomite, with sandstone and shale interbedded together close to the divide. Soil texture by hand assessment was normally loam to sandy loam over shale and clay over dolomite, loam to clay loam by granulometer analysis. Soil pH was low under shale normally without the influence of cultivation. Together with strong influence of human cultivation, soil pH was ~7 over shale and ~5 over the mixture of shale and dolomite. Actually due to the colluvial material input from further upslope, soils were influenced by dolomite, sandstone and shale together. Laboratory results showed low base saturation (<60%) with low CECs of 5.6–14.8 me/100g. The clay mineralogy for L2.20 showed a relatively high content of kaolinite, gibbsite and even some haematite in the bulk mineralogy, compared with the rest of the samples.

In the lower part, soils were mainly cultivated as sloping terraces. Due to the small area, only two augerings were observed in the field without any laboratory results. The influence from human activities was stronger. Soils were influenced by the mixture of shale, dolomite and sandstone. Soil texture assessment by hand was normally sandy loam. Soil was acidic (pH ~5.5) with 15-50% stoniness.

Figure 3.2.16. Bio-physical sequence along the eastern interfluve in Wang Jia Catchment, from Vinck (1999) adapted by Baire and Ghuisoland (2001)



Two transversal toposequences

The two transversal toposequences were noted as T1 and T2 in Figure 2.5. T1 transverses the upper part from eastern interfluve to the west interfluve and T2 transverses the middle part from western interfluve to the eastern interfluve. In total, eight augerings for T1 and seven augerings for T2 were made and soil information described (Table 3.2.8), among which two augerings for each toposequence were sampled for laboratory analysis (Table 3.2.7). Mineralogy data were shown in Table 3.2.3. Besides, three pits were sampled and analysed as WP. L2.3 and L1.6 included with T1. WP1, L1.21 and L2.17 were included in T2.

Table 3.2.8. The field description of two transversal toposequences, adapted from Vinck (1999).

Position	Augering N°	Depth (cm)	Texture	Colour	Stoniness*		pH
T1 eastern interfluve	T1.1	10	Loam	10YR 6/8	None	0	5.5
	T1.2	10	Loam	10YR 6/8	Shale	<15%	5.5
		65	Loam	10YR 6/8	Shale	<15%	5.5
		90	Loam	10YR 6/8	Shale	15-50%	5.5
	T1.3	20	Loam	10YR7/6	None	0	5
		90	Sandy loam	10YR5/8	None	0	5
T1 alluvial plain	L1.6	10	Sandy loam	10YR4/4	Sandstone	<15%	5.5-6
		50	Sandy loam	10YR4/6	Sandstone	<15%	5.5-6
		120	Sandy clay loam	10YR2/3	Sandstone	<15%	5.5-6
	T1.4	10	Sandy loam	10YR4/4	None	0	6.5
		25	Sandy loam	Transition	None	0	6.5
		50	Sandy loam	10YR4/6	Sandstone	<15%	6
		100	Sandy loam	5YR4/4	Sandstone	15-50%	6
	T1.5	40	Clay loam	10YR6/8	Shale	<15%	5
	T1.6	45	Clay loam	10YR7/4	Shale/dolomite	<15%	5
		70	Clay loam	10YR6/6	Shale/dolomite	<15%	5
		120	Clay loam	10YR6/8	Shale/dolomite	<15%	5
T1 western interfluve	T1.7	15	Clay	5YR 5/8	None	0	5
		60	Clay	5YR5/8	None	0	5
	T1.8	10	Clay loam	10YR 7/4	Shale	<15%	5
		30	Clay loam	10YR6/6	Shale	<15%	5

T2 west interfluve	WP1	10	Loam	10YR6/6	Shale	<15%	4.5
		80	Loam	10YR6/6	Shale	<15%	4.5
T2 western interfluve	WP1	150	Loam	10YR6/6	Shale	<15%	4.5
		190	Shale rock	-	-	~100%	-
		220	Shale rock	-	-	~100%	-
	T2.1	15	Loam	10YR6/6	Shale	15-50%	5
		30	Loam	10YR6/8	Shale	15-50%	5
		80	Loam	10YR6/8	Shale	<15%	5
		110	Clay loam	10YR6/8	Shale	<15%	5
	T2.2	40	Loam	10YR6/6	Shale	<15%	5
	T2.3	10	Loam	10YR6/6	Shale	<15%	5
		30	Loam	10YR6/6	Shale	<15%	5
		60	Loam	10YR6/8	Shale	<15%	5
	T2.4	30	Loam	10YR6/6	Shale	<15%	4.5
		50	Loam	10YR5/8	Shale	<15%	4.5
		100	Loam	10YR4/6	Shale	<15%	4.5
		120	Loam	7.5YR5/8	Shale	<15%	4.5
T2 alluvial plain	L1.21	15	Sandy loam	7.5YR4/4	dolomite/sandstone	<15%	7
		40	Sandy loam	10YR4/6	dolomite/sandstone	15-50%	7
		85	Sandy loam	7.5YR3/4	dolomite/sandstone	15-50%	7
		110	Sandy loam	7.5YR4/6	dolomite/sandstone	<15%	7
T2 eastern interfluve	T2.5	15	Clay loam	5YR4/6	Dolomite	15-50%	7.5-8
	T2.6	15	Clay loam	5YR3/6	Dolomite	15-50%	6.5
		70	Clay	5YR3/6	Dolomite	15-50%	7
		120	Clay	5YR3/6	Dolomite	15-50%	7
	T2.7	10	Sandy loam	7.5YR4/6	Shale/dolomite	15-50%	5
		45	Loam	7.5YR4/6	Shale/dolomite	<15%	5
		120	Clay loam	7.5YR5/8	Shale/dolomite	<15%	7
	L2.17	10	Sandy loam	7.5YR4/6	Shale	15-50%	5
		35	Loam	7.5YR4/6	Shale	<15%	5
		100	Loam	7.5YR5/8	Shale	<15%	7

In brief, soils in the upper part along T1 were under pine trees in the eastern interfluve, sloping terraces or terraces in the alluvial plain and sloping terraces in the western interfluve. Both the eastern and western interfluves were derived from shale, with low soil pH ~5-5.5, compared to the soils on the alluvial plain. Soil texture by hand assessment was more clay in the western interfluve than the eastern interfluve. There were dolomite outcrops down to the south in the eastern interfluve and up to the north in the western interfluve. These brought soils in T1 on the alluvial plain under the influence of shale, dolomite and sandstone. Soils on the alluvial plain were more neutral than on the two interfluves, with pH of 5-6.5. The two augerings (T1.6 and T1.7) analysed in laboratory were sampled on the western interfluve. The laboratory results further verified the field observations of low pH with base saturation of <60%. Soil organic carbon content was very low with values of 0.1-0.4%, indicating relatively low inherent soil fertility. The high CEC of T1.7 was unexpected. The clay mineralogy was dominated by a simple chlorite/illite assemblage, with a small amount of kaolinite and a trace gibbsite. A small amount of haematite was also found in the bulk mineralogy. Compared to the alluvial plain (L1.6), the soil on interfluve had inherently low fertility.

Regarding T2 in the middle part, soils were mainly cultivated as sloping terraces, except for T2.5 with bush and dolomite outcrops on the eastern interfluve close to the stream. The alluvial plain in this transverse is very narrow with steep side slopes. The western interfluve was dominated by shale with soil pH 4.5-5, while the eastern interfluve was dominated by dolomite at the slope foot and a mixture of shale and dolomite at the upslope with soil pH 5-8. Soil on the alluvial plain was neutral (~ pH 7). The augerings sampled for laboratory analysis are T2.5 and T2.6 on the eastern interfluve and WP1 at the western interfluve. T2.5, which was purely influenced by dolomite, had a pH of 7.3, WP1 over shale had pH values of 4.1-5.5 with base saturation <40%, while T2.6 was between 6.0-6.7, showing exactly the lithological influence on soil pH. Exchangeable Al^{3+} were found together with low pH and less base saturation in WP1. The high CEC value with considerable smectite content of WP1 was unexpected. These may be due to external materials from waterpond construction. The clay mineralogy for T2.5 and 2.6 was similar to those of the middle part for L1 and L2.

In summary, on the summit and alluvial plain, where the soil was influenced by sandstone, soil texture tended to be more sandy or silty, usually a silt loam. On the interfluves where soil was influenced by shale or dolomite, soil texture tended to be more clay-rich, usually silt loam to clay loam. Soil influenced by shale tended to be acidic, while dolomite tended to increase soil pH. Shale tended to be associated with yellowish, sandstone reddish brown and dolomite reddish soil colour. However, these three lithologies frequently mix as alluvium or colluvium in the alluvial plain or interfluve, which makes the circumstances very complex. Soil properties are very site-specific. The influence of human activities is different at different locations, which makes the interpretation of soil properties more difficult.

3.2.2.2. Six soil profile descriptions.

The soil horizons reflect the physical, chemical, and biological processes soils have undergone during their development. Horizon properties greatly influence how soils can and should be used. Based on the above augering results, six profiles pits were observed and described in March 2001 to represent the Wang Jia Catchment by Baire and Ghuisoland (2001).

Soil profile 1

The description of soil profile 1 is summarized in Figure 3.2.17. The laboratory analysis results are shown in Table 3.2.9. This soil profile of the sandstone mountain side was located on a 22° slope facing north and under a mixed clear forest of pine and alder with rhododendron. It presented a varied abundance of sandstone gravel, less weathered in the top horizon than at depth where there were also some stones, a silt loam texture, a yellowish brown colour in the first 33 cm (10YR) and an orange colour in the subsoil (7.5 YR). The soil organic matter distribution was limited to 0-23 cm and a moderately developed crumb structure in 0-8 cm.

Clay content increased from 10-28% down to 40 cm and then from 21-27 % down to 130 cm. Soil $pH_{(H2O)}$ was ~5, total organic carbon was 3.8% in 0-8 cm and 1.6% in 8-23 cm with a C/N ratio ~20. CEC at pH 7 started at 7.5 for soil with low clay and organic matter contents and reached ~15 me/100g for soil with higher clay (at depth) and/or organic matter (in topsoil of course) contents. Total P decreased from 87.6-40.8 mg of P_2O_5/100g soil, down to 95 cm.

There was little variation in clay mineralogy throughout the profile. The major (>50%) phase was an interstratified chlorite vermiculite. Illite was a relatively minor phase (5-25%) and showed evidence of slight vermiculitization. There was little evidence of kaolinite, although it may be present in trace amounts. The major iron oxide mineral detected was goethite, with lesser amounts of haematite.

This soil was acidic, hence the possibility of Al toxicity and had very low base saturation (10%). However, the effective CEC represented only 30-40% of the CEC at pH 7. It was base unbalanced and low in available phosphorus. According to the World Reference Base for Soil Resources (Decker *et al.,* 1998), the soil is a Hyperdystri-Episkeletic Regosol (Siltic) and according to the Soil Taxonomy (USDA, 1985), a Dystropept.

Figure 3.2.17. Soil profile 1 at the summit of Wang Jia Catchment.

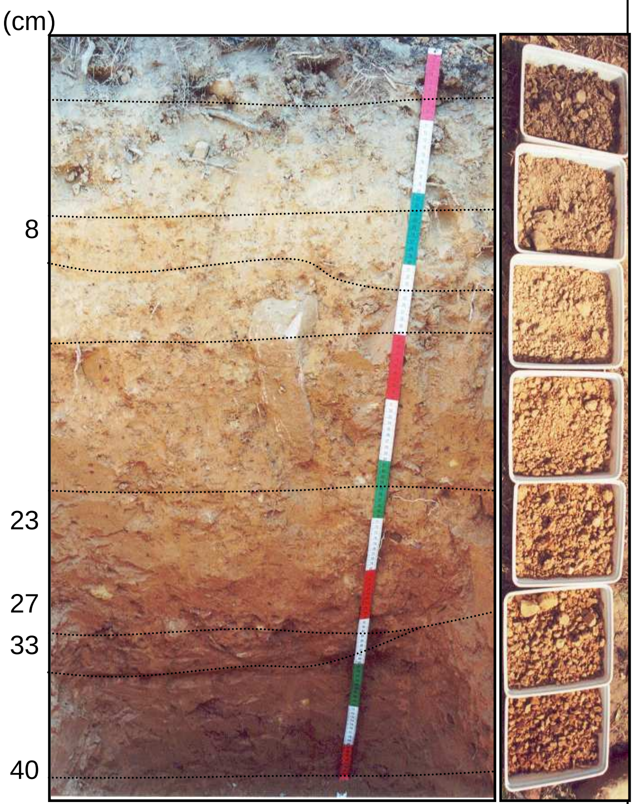
Location: summital relief with X = 287393 m and y = 2818249 m (UTM Co-ordinates) at altitude 2310 m

Context

Weather of the previous weeks: drought

Geomorphology: foot of a 200 m rectilinear (moutain) side with 22° slope facing north

Geology: occurrence of sandstone boulders



Description (0-130 cm)

Texture: 1. by touch: loamy in the top horizon(s) and “clay sandy” below.

2. by particle size analysis: silt loam to the limit of silty clay loam

Colour: yellowish brown-10YR (0-33 cm) then orange-7.5 YR with a few bright reddish brown-2.5 YR weathering spots >105 cm.

Structure: massive except the moderately developed 5 mm crumbly aggregates in 0-8 cm

Knife penetration test: easy (0-33cm) to difficult

General porosity: porous

Stoniness: 50% in 0-23 cm, 10% 23-40 cm, 30-40% 40-95 cm and 20% beneath a stony layer (95-105 cm) of sandstone gravel (stones and boulders) less weathered in the top horizons than at depth.

Root abundance and size: many fine to coarse 0-33 cm, common medium 33-65 cm then less below

Biological activity: low

Organic matter distribution: limited to 0-23 cm

Boundaries: smooth or wavy, clear.

Table 3.2.9. Laboratory results of Profile 1, adapted from Bock and Lacroix (2002).

Identification		RH	Particle size distribution				Acidity					Total organic matter				Exchangeable cations and CEC at pH 7									P_2O_5	
Hor.	depth	RH	Clay	Silt	Sand	FAO Texture	pH H_2O	pH KCl	Exch.acid.	Exch. Al	Kamprath index	tC	Estimated O.M.	tN	C/N	Ca	Mg	K	Na	Σ	CEC	V	Ca/Mg	Mg/K	Total	Avail.
	cm	%	%						me/100g		%	%				me/100g						%			mg/100g	
H1	0-8	2.4	9.3	70.5	20.3	SL	5.3	4.1	1.1	0.7	16	3.8	6.5	0.20	19.1	2.58	0.71	0.40	0.08	3.76	15.9	23.7	3.65	1.78	87.6	<2.3
H2	8-23	1.8	13.7	67.8	18.6	SL	5.0	3.9	2.4	1.6	60	1.6	2.8	0.07	21.4	0.51	0.21	0.24	0.08	1.03	9.8	10.5	2.37	0.89	73.6	<2.3
H3	23-33	1.3	16.6	67.4	16.0	SL	5.0	3.7	2.4	1.9	64	0.5	0.9			0.49	0.26	0.20	0.11	1.05	7.5	14.0	1.88	1.28	48.6	
H4	33-40	1.7	27.9	59.5	12.6	SCL	5.2	3.7	2.6	2.3	69	0.3	0.5			0.43	0.29	0.24	0.09	1.04	9.9	10.5	1.48	1.22	50.0	
H5	40-65	1.7	20.6	64.2	15.3	SL	5.1	3.8	3.1	2.7	77	0.4	0.7			0.22	0.28	0.20	0.10	0.79	10.4	7.7	0.78	1.39	55.7	
H6	65-95	1.8	24.1	59.2	16.8	SL	5.2	3.8	2.6	2.3	78	0.3	0.5			0.11	0.25	0.19	0.09	0.63	11.3	5.6	0.42	1.33	40.8	
H7	Gravel and stone (90%) - Sandstone																									
H8	105-130	2.1	26.9	61.3	11.8	SL	5.2	3.8	2.9	2.6	69	0.4	0.7			0.19	0.69	0.19	0.08	1.14	13.4	8.5	0.27	3.61	47.1	

RH=residual humidity SL=silt loam SCL=silty clay loam Kamprath index=[exch. Al/(exch. Al+Σ)] x 100 Estimated organic matter=tC x 1.72 Σ=sum of exch. Cations V=base saturation rate = (S/CEC) x 100 Avail.=available

Soil profile 2

The description of soil profile 2 is summarized in Figure 3.2.18. The laboratory analysis results are shown in Table 3.2.10. This soil of the upper western interfluve was located in the middle of a rectilinear slope on shale with an average slope angle of 5° and cultivated on sloping terraces. It presented a common stoniness (20%) of weathered shale gravel in 0-75 cm layer and a more abundant one beneath, a silt loam texture, a yellowish brown to yellow orange colour (10YR), an organic matter appearance down to 75 cm and a moderately developed crumb structure at 0-5 cm.

Clay content increased from 9.5-19% down to 100 cm depth and beneath the stony layer (colluvial materials) from 17.5-23.9% down to 190 cm depth. Soil pH $_{(H20)}$ decreased from 5.6 to 5.1 from 0 to100 cm and then increased to 6.6. Total organic carbon was 3.5% at 0-5 cm and 1.2 at 5-75 cm, with a C/N ratio ~17. CEC was higher (15-20 me/100g of soil) in the subsoil and organic horizons than at mid-depth (6.8 me/100g of soil for 19% clay at 100 cm) and total phosphorus reached 121.3 mg of P_2O_5/100g of soil at 40-75 cm.

Soil clay mineralogy was dominated by a simple chlorite/illite assemblage throughout the profile, with chlorite probably being the major component. The peaks were always exceedingly sharp and well defined, suggesting that the clays have been little influenced by weathering. There was no evidence for kaolinite. Goethite was the major iron oxide mineral detected, with smaller amounts of haematite and lepidocrocite. The latter may account for the orange soil colour.

This soil was acidic, with low base saturation (10%) but the effective CEC represented only 25-40% of CEC at pH 7. It was base unbalanced and low in available P. According to the WRBSR, it is an Orthidystri-Endoskeletic Regosol (Siltic,… Magnesic and Anthric) and according to the Soil Taxonomy, a Dystropept.

Figure 3.2.18. Soil profile 2 at the upper western interfluve of Wang Jia Catchment.

Location: western upper part with X = 287203 m and y = 2818651 m at altitude 2160 m

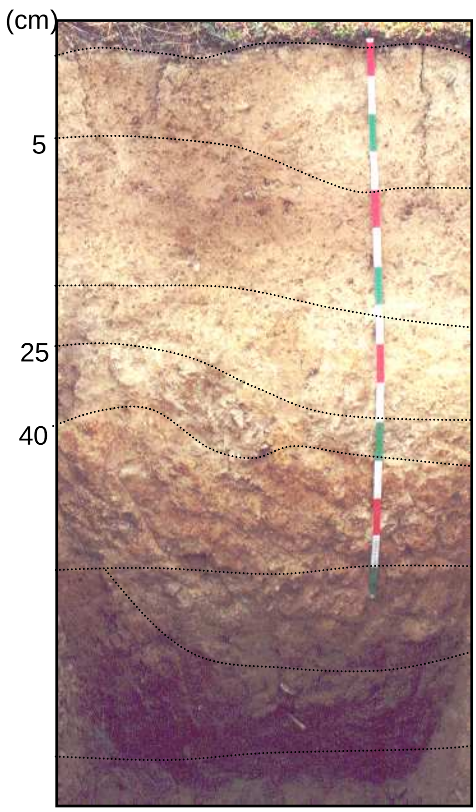
Context

Weather of the previous week: drought

Geomorphology: middle of a rectilinear slope with an average 5° slope

Geology: shale outcrops

Land cover: cropland



Description (0-190 cm)

Texture: 1. by touch: loamy in the top horizon(s) and clay loam below.

2. by particle size analysis: silt loam

Colour: yellowish brown to yellow orange-10YR with some yellowish -2.5 Y weathering spots below 110 cm.

Structure: massive except the moderately developed 5 mm crumbly aggregates in 0-5 cm

Knife penetration test: easy (0-75 cm) to difficult

General porosity: slightly porous

Stoniness: <20% in 0-75 cm and >50% of weathered shale gravel 75-100 cm and beneath a stony layer (100-110 cm)

Root abundance and size: common very fine to medium in 0-75 cm and then progressively decreasing

Biological activity: very high in the top horizon

Organic matter distribution: 1. by observation: limited to the top horizon (0-5 cm)

Table 3.2.10. Laboratory results of Profile 2, adapted from Bock and Lacroix (2002).

Identification		RH	Particle size distribution				Acidity					Total organic matter				Exchangeable cations and CEC at pH 7									P_2O_5	
Hor.	depth	RH	Clay	Silt	Sand	FAO Texture	pH H_2O	pH KCl	Exch.acid.	Exch. Al	Kamprath index	tC	Estimated O.M.	tN	C/N	Ca	Mg	K	Na	Σ	CEC	V	Ca/Mg	Mg/K	Total	Avail.
	cm	%	%						me/100g		%	%				me/100g						%			mg/100g	
H1	0 - 5	2.1	9.5	72.3	18.2	SL	5.6	4.5	0.2	0.0	0	3.5	7.0	0.20	17.4	4.41	2.20	0.74	0.11	7.45	15.2	49.0	2.00	2.97	93.9	<2.3
H2	.5 - 40	1.4	11.3	73.2	15.6	SL	5.2	4.1	0.9	0.6	19	1.2	2.4	0.07	17.0	1.28	0.65	0.32	0.12	2.36	8.5	27.9	1.95	2.05	67.9	<2.3
H3	40 -75	1.7	15.9	75.6	8.6	SL	5.4	4.1	1.1	0.8	29	1.2	2.4	0.04	31.2	0.88	0.58	0.32	0.10	1.86	9.4	19.8	1.52	1.83	121.3	<2.3
H4	75 - 100	1.2	19.0	71.6	9.4	SL	5.1	3.7	1.2	0.8	32	0.4	0.8			0.61	0.80	0.16	0.09	1.67	6.8	24.7	0.75	4.90	90.6	
H5	Gravel and stones (85%) - Shale																									
H6	110 - 140	1.8	17.5	70.3	12.2	SL	5.9	4.5	0.1	0.0	0	0.1	0.2			1.55	1.86	0.28	0.09	3.78	13.4	28.2	0.83	6.51	65.2	
H7	140 - 170	2.3	15.7	75.8	8.5	SL	6.2	4.9	0.1	0.0	0	0.3	0.6			2.25	2.71	0.24	0.10	5.28	23.0	23.0	0.83	11.41	76.6	
H8	170 - 190	3.2	23.9	75.6	0.6	SL	6.6	5.4	0.1	0.1	1	0.4	0.8			2.81	4.56	0.29	0.12	7.78	19.6	39.6	0.61	15.65	83.3	

RH=residual humidity SL=silt loam Kamprath index=[exch. Al/(exch. Al+Σ)] x 100 Estimated organic matter=tC x 1.72 Σ=sum of exch. Cations V=base saturation rate = (S/CEC) x 100 Avail.=available

Soil profile 3

The description of soil profile 3 is summarized in Figure 3.2.19. The laboratory analysis results are shown in Table 3.2.11. This soil of the dolomite environment was located at the foot of a 250 m rectilinear slide, with an 39° slope facing north and described in a quarry. It presented a common stoniness (15%) of weathered shale and dolomitic gravel, a silt loam texture, a bright brown colour in 0-37 cm (7.5YR) and a reddish brown subsoil colour (2.5YR). Organic matter was appeared to >54 cm. There was a high level of biological activity down to 37 cm, a moderately developed crumb structure and a weak reaction to HCl.

Clay content was ~12% in the first 37 cm and 20/25% below. Soil pH $_{(H2O)}$ was ~7.5 and 6.4 with traces of carbonates, total organic carbon was 3.3% between 15-37 cm with a C/N ratio of 21 and 0.8 % below 54 cm. CEC reflects the clay and organic matter content, ranging from 12.8-17.0 me/100g of soil, total P was ~80 mg P_20_5/100g of soil.

Clay mineralogy was dominated by an interstratified chlorite/vermiculite mineral assemblage throughout the profile. Illite was also present throughout the profile, but was very much subordinate to the chloritic mineral. The XRD traces suggested the presence of a small amount of a kaolin, but it was uncertain. The main iron oxide mineral was goethite, but minor amounts of haematite were also present. This soil was neutral/calcic (dominated by exchangeable Ca) to slightly acidic, fairly uniform organic matter content in colluvial materials, highly (topsoil) to moderately base saturated, base unbalanced and low in available P.

According to the WRBSR, it is an Orthieutri-Thaptoluvic Regosol (Abruptic and Siltic) or a Orthieutri-Rhodic Luvisol (Siltic). According strictly to the definitions of the Soil Taxonomy, it is a fine-loamy, mixed, hyperthermic Typic Rhodustalf.

Figure 3.2.19. Soil profile 3 at the limit between the upper and middle part of Wang Jia Catchment.

Location: limit between the upper and middle part along the track to the guard's house. X = 287235 m and y = 2819003 m at altitude 2070 m

Context

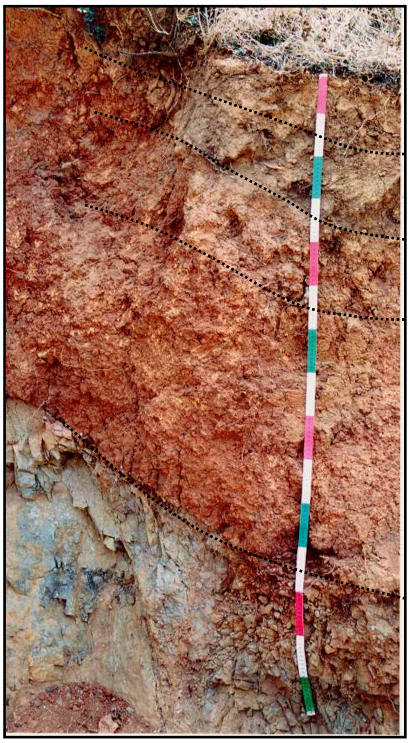
Weather of the previous week: drought

Geomorphology: foot of a 250 m rectilinear with an average 39° slope facing north

Geology: dolomite outcrops

Land cover: quarry of secondary importance

Human influence: terraces



Description (0-114 cm)

Texture: 1. by touch: loamy in the top 37 cm and clayey below.

2. by particle size analysis: silt loam

Colour: bright brown – 7.5 YR (0-37 cm) with some orange-5YR "spots" of weathered shale, then reddish brown - 2.5 YR

Structure: moderately developed 1 mm crumbly aggregates

Knife penetration test: difficult to very difficult

General porosity: porous

Stoniness: 15%, mainly gravel of weathered shale and dolomite

HCl reaction: yes but weak for the fine earth

Root abundance and size: common very fine to coarse (0-37 cm) and less below

Biological activity: high down to 37 cm

Organic matter distribution: 1. by observation: mainly in 0-37 cm

2. by total carbon analysis: down to >54 cm

Boundaries: irregular, clear for the first two, gradual for the third one.

Table 3.2.11. Laboratory results of Profile 3, adapted from Bock and Lacroix (2002).

Identification		RH	Particle size distribution				Acidity				Total $CaCO_3$	Total organic matter				Exchangeable cations and CEC at pH 7									P_2O_5	
Hor.	depth	RH	Clay	Silt	Sand	FAO Texture	pH H_2O	pH KCl	Exch.acid.	Exch. Al	Total $CaCO_3$	tC	Estimated O.M.	tN	C/N	Ca	Mg	K	Na	Σ	CEC	V	Ca/Mg	Mg/K	Total	Avail.
	cm	%	%						me/100g		%	%				me/100g						%			mg/100g	
H1	0-15	2.1	12.1	60.4	27.5	SL	7.5	6.7			0.3	1.7	2.9	0.1	16.5	9.96	2.30	0.43	0.09	12.79	12.8	99.6	4.32	5.30	74.4	<2.3
H2	15-37	2.6	12.1	67.8	20.1	SL	7.4	6.6			0.1	3.3	5.7	0.2	21.1	14.18	2.69	0.27	0.10	17.23	17.0	ss	5.27	9.86	93.3	<2.3
H3	37-54	2.6	20.5	64.2	15.3	SL	6.4	5.1	0.0	0.0		1.1	1.9	0.1	16.7	5.16	2.82	0.27	0.13	8.37	14.0	59.8	1.83	10.29	81.1	<2.3
H4	54-114	2.9	25.0	62.0	13.0	SL	6.4	5.5	0.0	0.0		0.8	1.4			4.36	2.53	0.26	0.11	7.26	14.7	49.3	1.72	9.59	81.1	

RH=residual humidity SL=silt loam Kamprath index=[exch. Al/(exch. Al+Σ)] x 100 Estimated organic matter=tC x 1.72 Σ=sum of exch. Cations V=base saturation rate = (S/CEC) x 100 Avail.=available

Soil profile 4

The description of soil profile 4 is summarized in Figure 3.2.20. The laboratory analysis results are shown in Table 3.2.12. This soil of the middle eastern interfluve was located on a convex position with a local 8° slope and was cultivated under chestnut trees after stone removal.

The profile presented an abundant stoniness of weathered shale and sandstone gravel with an extreme gravelly layer (including dolomite) between 85 and 100 cm and a double horizons with silt loam or silty clay loam textures. The colour was brown in the first 20 cm (7.5YR), (dark) reddish brown at mid-depth (2.5YR) and yellowish brown at depth (10YR). Organic matter distribution was limited to 0-25 cm and there was a coarse subangular structure in the first 20 cm.

Clay content increased from 21.4-32.1% down to 60 cm and was slightly lower beneath. Soil $pH_{(H2O)}$ increased with depth from 5.0 to 6.0. Total organic carbon was 2.3% and 1.8% for the two first horizons (0-25 cm) with a C/N ratio of ~15. CEC was 20.9 in topsoil, 28.6 in the reddish brown horizon and 34.0 me/100g in the yellowish brown horizon. Total P reached 137.2 in topsoil, but was generally ~80 mg P_2O_5/100g in the rest of the profile. The clay fraction contained abundant halloysite. Throughout the profile, chlorite/vermiculite, illite and halloysite were co-dominant. In addition, gibbsite occurred in subordinate amounts down to 95 cm. Goethite and haematite were the major iron oxide minerals.

The soil was acidic, low base saturated (30%), but the effective CEC represented only 20-30% of the CEC at pH 7. It was base unbalanced and low in available P. According to the WRBSR, it is an Orthidystri-Thaptoluvic Regosol (Skeletic, Siltic and Anthric) or an Orthidystri-Rhodic Luvisol (Skeletic, Siltic and Anthric). According strictly to the definitions of the Soil Taxonomy, it is a fine-loamy, mixed, hyperthermic, Typic Haplustalf.

Figure 3.2.20. Soil profile 4 located in the middle part of Wang Jia Catchment.

Location: eastern interfluve of the middle part. X = 287118 m and y = 2819417 m at altitude 2020 m

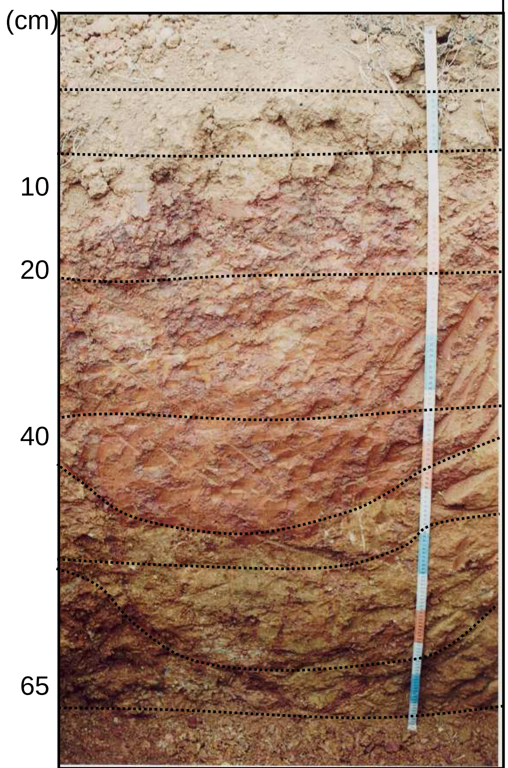
Context

Weather of the previous week: drought

Geomorphology: convex position with a local 8° slope

Geology: dolomite "outcrops" in gullies

Land cover: cropland and chestnut trees



Description (0-150 cm)

Texture: 1. by touch: loamy (0-20 cm), clay (20-85 cm) and clay loam below

2. by particle size analysis: silt loam (0-20 cm, 60-85 cm and 125-150 cm) and silty clay loam (20-60 and 100-125 cm)

Colour: brown – 7.5 YR (0-20 cm), (dark) reddish brown – 2.5 YR (20-85 cm) and yellowish brown – 10 YR (down to 150 cm)

Structure: (very) coarse subangular blocky (0-20 cm) and then massive

Knife penetration test: very difficult at topsoil to difficult below 95 cm

General porosity: slightly porous

Stoniness: abundant weathered shale and sandstone gravel

Root abundance and size: very few and very fine

Biological activity: low

Organic matter distribution: 1. by observation: not described

2. by total carbon analysis: down to 40 cm

Boundaries: smooth or wavy, abrupt (at 85 cm) to clear or gradual.

Table 3.2.12. Laboratory results of Profile 4, adapted from Bock and Lacroix (2002).

Identification		RH	Particle size distribution				Acidity					Total organic matter				Exchangeable cations and CEC at pH 7									P_2O_5	
Hor.	depth	RH	Clay	Silt	Sand	FAO Texture	pH H_2O	pH KCl	Exch.acid.	Exch. Al	Kamprath index	tC	Estimated O.M.	tN	C/N	Ca	Mg	K	Na	Σ	CEC	V	Ca/Mg	Mg/K	Total	Avail.
	cm	%	%						me/100g		%	%				me/100g						%			mg/100g	
H1	0-15	3.0	21.4	60.9	17.7	SL	5.0	4.0	0.9	0.6	9	2.3	4.5	0.2	15.1	4.31	1.09	0.49	0.00	5.89	20.9	28.2	3.95	2.22	137.2	<2.3
H2	15-20	3.1	26.1	58.2	15.7	SL	5.0	4.0	0.7	0.5	8	1.8	3.6	0.1	14.8	4.14	1.17	0.46	0.11	5.88	18.5	31.8	3.52	2.53	122.1	<2.3
H3	20-40	3.2	29.3	64.6	6.1	SCL	5.9	5.2	0.1	0.0	0	0.7	1.4			5.30	2.13	0.27	0.12	7.81	28.6	27.3	2.48	8.00	88.4	
H4	40-65	2.5	32.1	64.2	3.7	SCL	6.0	5.8	0.2	0.0	0	0.2	0.3			10.32	1.84	0.19	0.14	12.48	24.6	50.7	5.59	9.86	75.2	
H5	65-85	2.5	26.1	60.8	13.2	SL	6.0	5.8	0.2	0.0	0	0.2	0.4			4.20	1.99	0.19	0.14	6.51	23.1	28.2	2.11	10.66	79.0	
H6	Gravel and stones - Sandstone and shale																									
H7	95-125	3.2	30.6	68.9	0.5	SCL	6.1	6.0	0.1	0.0	0	0.3	0.6			4.89	2.26	0.20	0.18	7.53	34.0	22.2	2.16	11.22	100.4	
H8	125-150	2.6	24.1	72.0	3.9	SL	5.9	5.8	0.1	0.0	0	0.2	0.4			5.07	1.85	0.20	0.13	7.25	32.2	22.5	2.74	9.05	75.2	

RH=residual humidity SL=silt loam SCL=silty clay loam Kamprath index=[exch. Al/(exch. Al+Σ)] x 100 Estimated organic matter=tC x 1.72 Σ=sum of exch. Cations V=base saturation rate = (S/CEC) x 100 Avail.=available

Soil profile 5

The description of soil profile 4 is summarized in Figure 3.2.21. The laboratory analysis results are shown in Table 3.2.13. This soil of the middle eastern shoulder was located on the middle of a slope on dolomite facing west at a slope inflexion between 11-42° and was cultivated on sloping terraces.

The profile had ~10% shale, sandstone and dolomite gravel, with some boulders between 20 and 35 cm. The texture was silt loam down to 83 cm and silty clay loam below. The colour was bright reddish brown (5YR) in the first 35 cm and (dark) reddish brown (2.5YR) below. Organic matter distribution went down to 55 cm and even 83 cm. There was a moderately weakly developed crumb structure (0-20 cm) and a positive reaction to HCl.

Clay content increased from 19.7-28.8% down to 126 cm depth. Soil $pH_{(H2O)}$ ranged from 7.8-6.9 with carbonate traces, total organic carbon was ~1.2% down to 55 cm and 0.7% 55-83 cm with a C/N ratio of ~15. CEC increased from 12.7-19.4 me/100g with percentage clay and total P content ranged from 110-133 mg P_2O_5/100g. Clay mineralogy was similar to that of profile 4. This soil was neutral/calcic, fairly uniform organic matter content in colluvial materials, highly to moderately base saturated, base unbalanced with a relatively high importance of magnesium and low available P.

According to the WRBSR, the soil is a Silti-Thaptoluvic Regosol (Anthric) or a Silti-Rhodic Luvisol (Anthric). According strictly to the definitions of the Soil Taxonomy, it is a fine-loamy, mixed, hyperthermic, Typic Haplustalf.

Figure 3.2.21. Soil profile 5 at the middle eastern interfluve of Wang Jia Catchment.

Location: eastern interfluve of the middle part. X = 287045m and y = 2819393 m at altitude 1980 m

Context

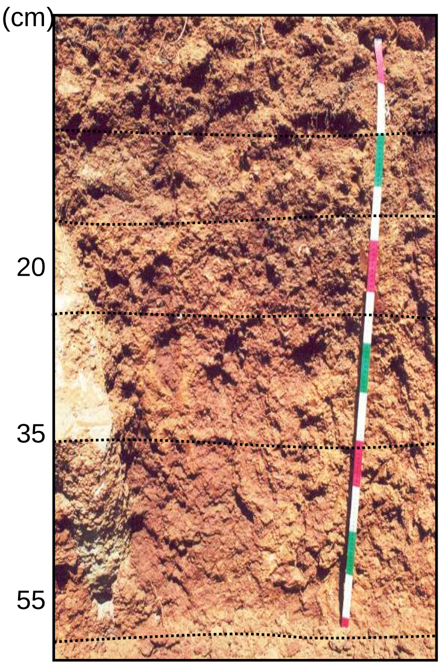
Weather of the previous weeks: drought

Geomorphology: middle of a slide facing west, at a slope inflexion between 11° and 42° (eastern shoulder)

Geology: dolomite outcrops and boulders

Land cover: cropland

Human influence: terraces



Description (0-126 cm)

Texture: 1. by touch: clay loamy

2. by particle size analysis: silt loam down to 83 cm and silty clay loam below

Colour: bright reddish brown – 5YR (first 35cm) and (dark) reddish brown – 2.5 YR with some (yellow) orange “spots” of weathered shale

Structure: crumb, moderate (0-20 cm) to weak

Knife penetration test: easy (0-20 cm) to (very) difficult

General porosity: slightly porous

Stoniness: around 10% (but 30% between 20-35 cm including boulders) of shale, sandstone and dolomite gravel; the latter lithology being very weathered at depth

Root abundance and size: many very fine in the top horizon (20 cm) and very few below

Biological activity: low

Organic matter distribution: 1. by observation: mainly in the top horizon(s)

2. by total carbon analysis: down to 83 cm

Boundaries: smooth, clear or gradual at depth.

Table 3.2.13. Laboratory results of Profile 5, adapted from Bock and Lacroix (2002).

Identification		RH	Particle size distribution				Acidity		Total $CaCO_3$	Total organic matter				Exchangeable cations and CEC at pH 7									P_2O_5	
Hor.	depth		Clay	Silt	Sand	FAO Texture	pH H_2O	pH KCl		tC	Estimated O.M.	tN	C/N	Ca	Mg	K	Na	Σ	CEC	V	Ca/Mg	Mg/K	Total	Avail.
	cm	%	%						%	%				me/100g						%			mg/100g	
H1	0-20	2.4	19.7	64.4	15.9	SL	7.8	7.1	1.5	1.3	2.6	0.1	14.4	7.34	2.97	0.33	0.13	10.76	12.7	84.9	2.47	9.11	114.0	<2.3
H2	20-35	2.8	19.5	64.1	16.4	SL	7.8	7.1	1.1	1.2	2.4	0.1	14.7	8.69	2.88	0.16	0.08	11.82	15.6	75.5	3.01	17.48	109.7	<2.3
H3	35-55	3.5	20.1	69.4	10.5	SL	7.5	6.5	0.0	1.2	2.3	0.1	12.4	8.28	3.47	0.19	0.15	12.08	18.7	64.7	2.38	18.37	133.1	<2.3
H4	55-83	3.8	26.7	63.8	9.5	SL	6.9	6.1		0.7	1.3			5.72	2.55	0.15	0.17	8.59	19.4	44.3	2.24	16.78	123.7	
H5	83-126	3.8	28.8	68.2	3.0	SCL	7.1	6.5	0.0	0.4	0.7			6.05	2.45	0.17	0.14	8.80	18.3	48.0	2.47	14.19	109.1	

RH=residual humidity SL=silt loam SCL=silty clay loam Estimated organic matter=tC x 1.72 Σ=sum of exch. Cations V=base saturation rate = (S/CEC) x 100 Avail.=available

Soil profile 6

The description of soil profile 6 is summarized in Figure 3.2.22. The laboratory analysis results are shown in Table 3.2.14. This soil of the catchment outlet near the village was located near the top of a 100 m rectilinear slide on shale with a 6° slope and was cultivated on terraces.

The soil had a stoniness of ~10% in 0-80 cm and ~30% between 80-115 cm, of slightly weathered shale and dolomite gravel, then below it was ~80% weathered shale and sandstone gravel and stones. The texture was silt loam and the colour was yellowish brown to yellow orange (10YR) in the first 45 cm and yellow (2.5 and 5Y) to a grey horizon with some mottles. Organic matter distribution went down to 45 cm and even 115 cm. This soil had a moderately developed subangular blocky structure and a positive reaction to HCl.

Clay content increased from 15.0-21.6% down to 115 cm and was a slightly lower beneath. Soil pH $_{(H2O)}$ was ~8.0 with ~8.0% of carbonates in the first 80 cm and some traces below. Total organic carbon decreased from 2.3-0.9% down to 115 cm, with a C/N ratio of 11. CEC was ~20 in topsoil and decreases to 13 me/100g at depth. Total P content was >180 mg of P_20_5/100g in the first 45 cm and still ~100 below. Clay mineralogy was similar to that of profiles 4 and 5. This soil was calcareous, highly base saturated, fairly regular decrease in organic matter content with depth, base unbalanced and with some available P. According to the WRBSR, it is an Endogleyi-Calcaric Regosol (Siltic and Anthric) and according to the Soil Taxonomy, an Eutropept.

Figure 3.2.22. Soil profile 6 in the lower part of Wang Jia Catchment.

Location: western interfluve of the middle part. X = 286775 m and y = 2819737 m at altitude 1890 m

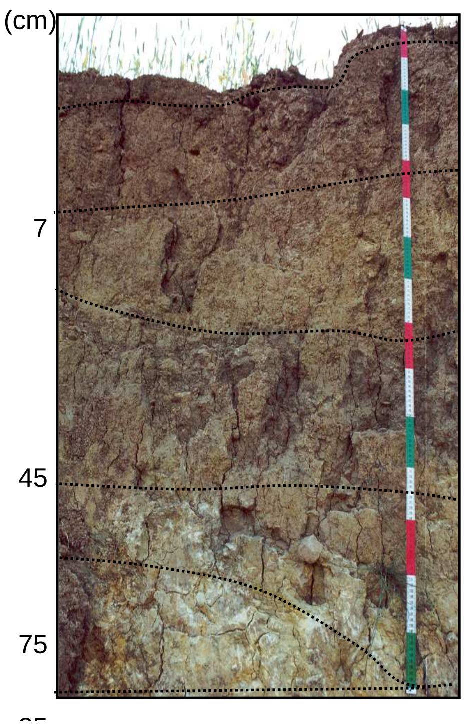
Context

Weather of the previous week: drought

Geomorphology: near the top of a 100 m rectilinear slide with a 6° slope

Geology: shale outcrops

Land cover: cropland



Description (0-150 cm)

Texture: 1. by touch: not described

2. by particle size analysis: silt loam

Colour: yellowish brown to yellow orange– 10YR (first 45 cm) and yellow – 2.5 YR and 5 YR down to a grey horizon, with some spots (7-115 cm) of same colour but stronger chroma

Structure: subangular, moderately developed

Knife penetration test: difficult to very difficult

General porosity: very porous

Stoniness: 10% in the first 80 cm and 30% between 80-115 cm of slightly weathered shale and dolomite gravel, then below 80% of weathered shale and sandstone gravel and stones

HCl reaction: high in the first 80 cm

Root abundance and size: common in 0-7 cm and then progressively decreasing, mainly very fine

Biological activity: relatively low in the lowest horizons

Organic matter distribution: 1. by observation: mainly in the top horizon(s)

2. by total carbon analysis: down to 115cm

Boundaries: smooth or wavy but irregular at depth, clear.

Table 3.2.14. Laboratory results of Profile 6, adapted from Bock and Lacroix (2002).

Identification		RH	Particle size distribution				Acidity		Total $CaCO_3$	Total organic matter				Exchangeable cations and CEC at pH 7									P_2O_5	
Hor.	depth	RH	Clay	Silt	Sand	FAO Texture	pH H_2O	pH KCl	Total $CaCO_3$	tC	Estimated O.M.	tN	C/N	Ca	Mg	K	Na	Σ	CEC	V	Ca/Mg	Mg/K	Total	Avail.
	cm	%	%						%	%				me/100g						%			mg/100g	
H1	0-7	2.6	15.0	69.1	15.9	SL	8.0	7.6	6.9	2.3	4.6	0.2	11.1	52.27	2.27	0.75	0.11	55.41	20.8	ss.	23.00	3.03	259.1	4.6 - 6.9
H2	7-45	2.6	19.9	70.3	9.8	SL	8.1	7.6	8.1	1.3	2.6	0.1	10.8	56.73	3.37	0.34	0.06	60.50	20.2	ss.	16.82	10.04	183.9	<2.3
H3	45-80	2.1	17.1	71.8	11.1	SL	8.2	7.7	10.3	0.8	1.6			35.55	3.55	0.22	0.14	39.46	18.5	ss.	10.00	16.28	111.1	
H4	80-115	2.4	21.6	65.7	12.7	SL	8.0	7.4	0.1	0.9	1.8			9.25	2.39	0.18	0.11	11.93	16.4	72.7	3.86	13.09	93.3	
H5	115-135	2.2	13.9	78.0	8.1	SL	8.0	7.4	0.1	0.2	0.4			7.46	2.36	0.15	0.12	10.09	11.8	85.8	3.15	15.63	48.8	
H6	135-150	2.3	16.7	74.3	9.0	SL	8.0	7.6	0.3	0.1	0.2			8.03	2.60	0.17	0.15	10.94	12.6	87.1	3.09	15.11	100.4	

RH=residual humidity SL=silt loam Estimated organic matter=tC x 1.72 Σ=sum of exch. Cations V=base saturation rate = (S/CEC) x 100 Avail.=available

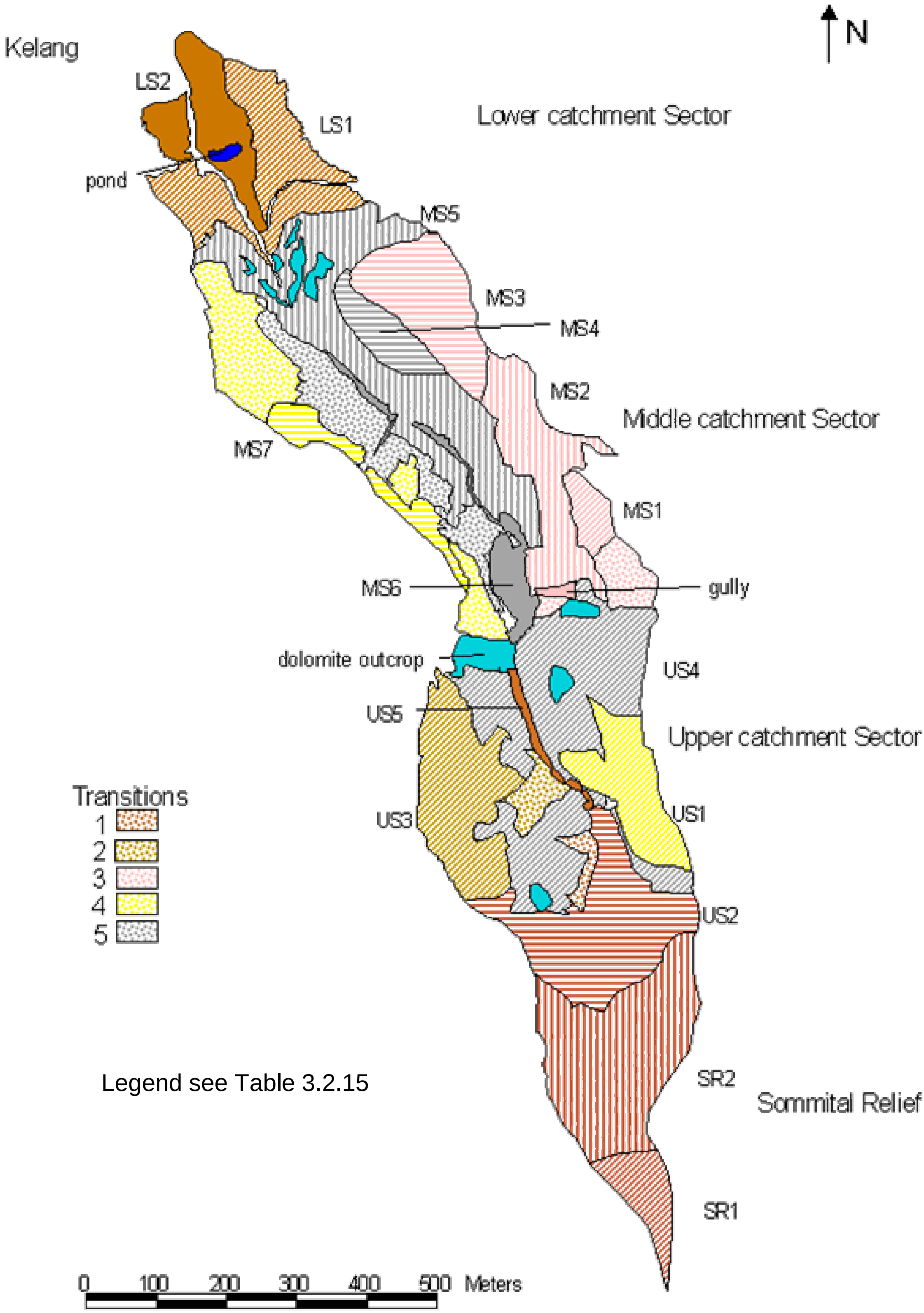
3.2.3 Geomorphopedological unit synthesis

3.2.3.1 Geomorphopedological unit identification

In order to characterize and predict soil properties in such a way that useful statements can be made about land use potential and responses to changes in management, it is necessary to determine the soil distribution and to divide it into relatively homogeneous units. However, each soil property usually changes fairly gradually in both vertical and horizontal directions. Change in one property will not necessarily be in phase with change in another, so that identical combinations do not necessarily reappear in the landscape. Nevertheless, soil individuals are defined, their boundaries are transitional and intergrades are common. Normally soil units are defined according to the project purpose. Based on the field surveys and geomorphopedological description, a geomorphopedological sketch map was produced by Bock and Lacroix (2002) (Figure 3.2.23).

In Wang Jia Catchment, the soil-forming factors are very changeable as described in Sections 3.2.1 and 3.2.2. Soils can be different even several metres apart. Soil property differences in such a small-scale are mostly due to the changes of topography, parent materials and the effects of vegetation or past human management. Parent materials and temperature often vary on large scales, but in such a small catchment as Wang Jia the greatest differences occurred in lithology. Complicated topographic changes and human cultivation measurements were also involved in this catchment. Steep slopes generally encourage erosion of the surface layers and allow less rainfall to enter the soil before running off, thus decreasing soil formation rates, leading to soil removal. Less effective moisture on the steeper slopes also results in a more sparse and less diverse plant cover. Colluvial parent materials are being carried and deposited at downslope positions, which are principally coarse and stony. Colluvial deposits tend to be unstable and prone to slumping and landslides (especially adjacent to the major gully in the middle part). Soils on steep terrain have relatively shallow, poorly-differentiated soil profiles compared to nearby soil on more level terrain. Alluvium along the stream tends to be very productive. Based on these observations, 16 geomorphopedological units and five transitional units were identified in Wang Jia Catchment by Gembloux Agricultural University. These 16 units comprised of two units in the summital relief (UR), five in the upper sector (US), seven in the middle sector (MS) and two in the lower sectors (LS).

Figure 3.2.23. Geomorphopedological sketch of Wang Jia Catchment adapted from Bock and Lacroix, Gemboux Agricultural University (2002).



3.2.3.2 Geomorphopedological unit synthesis

The legend of Figure 3.2.23 is presented in Table 3.2.15, which presents the field (physiographical and morphological) and laboratory information (mineralogical and physico-chemical) which explain the rock-relief-soil-land use relations and justify the mapping units. The potential basis of a Land Information System (LandIS), references to soil pits and/or augerings and/or a soil fertility evaluation plot are given and limiting factors suggested. Reference plots ensure the links with data gained from field measurements and farmers' survey card later in this study (Figure 3.2.24). All the data summarized in Table 3.2.15 were analysed with soil sample Sets 1, 2 and 3. The crop yield data were obtained from interviews with local farmers by Baire and Ghuisoland (2001).

For presentation, the data in Table 3.2.15 were largely condensed. A relevant database including many themes actually exists in GIS files, including soil and crop data from 1999 to 2002. Selected data can be extracted from these files according to different future uses. Socio-economic data could also be linked to this database for further evaluation and modelling land use changes. To analyse crop-soil interactions, soil fertility parameters were extracted and are presented in Table 3.2.16. The soil data presented were from soil sample Set 3 and crop data were from 1999 on-farm measurements. These data can be used as a reference base for similar catchments in this region and for monitoring soil fertility (quality) changes. These data are only valid for some geomorphopedological units that include any of the 30 plots. However, other geomorphopedological units may include of the 100 plots, and their potential in crop production is analysed with 100 plots data in Sections 3.3 and 3.4.

Selected soil fertility parameters from Table 3.2.16 are presented in Figure 3.2.25. Firstly, the standard deviation of each soil parameter is relatively large, this may be partly due to the small data population. This is true for all parameters in Table 3.2.16. However, there are differences between different units. SR2, US3, MS2 and MS3 have relatively low pH due to influence of sandstone and/or shale, while US2, US5, MS4, MS5, MS6, LS1 and LS2 are more neutral with relatively high pH. Total exchangeable cation content increases from summit to lower catchment, indicating the increase of soil fertility. MS4, MS5, MS6, LS1 and LS2 have relatively high total cation contents,

Table 3.2.15. Physical characteristics of Wang Jia catchment and sketch units largely adapted from Baire & Ghuisoland (2001).

	Dominant lithology	Physiographic position	Slope		Mapping units	Land Cover	Reference augerings or profiles	Soil stoniness		Soil colour	Soil thickness (cm)	Mineralogy at depth (Bulk - clay)	Texture & clay %	TOC %	Synthesis parameters		Limiting factors	Reference plots composite samples	TOC %	pH H_2O	Avail. K me/100g	Avail. P mg/100g	Corn cob Fresh weight kg/m²
			Form	%				Nature	Abund.						pH H_2O	CEC (me/100g)							
Summital Relief	Sandstone	Mountain side	Linear	20 - 50		Outcrops Mixed forest	Augering L1.2 Profile P1	Sd	Stony	(d)(y)Br/Br,O	0 → 100		SL 9 / 27	3.8…1.6	~ 5.2	16/8/2013	Altitude, outcrops, (slope), stoniness, (soil thickness), pH...						
	Sandstone Shale			30 - 70		Outcrops Mixed forest, aband. terraces	Augerings L1.3, L1.4	Sd - (Sh)	(Sl.) stony	(y)Br/yO	20 → 120	Q, F - I, C	SL 15	1.4	5.6 / 6.0	14	Altitude, slope, (soil thickness), pH	1.1, 1.2	1.3 - 1.9	5.5 - 6.0	0.26 - 0.52	2.1	
Upper Catchment Sector	Shale	E. divide & side	Convex, Linear	15 30 - 70		Outcrops pine tree, grass, [crops on sloping terraces]	Augerings L2.1→ L 2.3 → L2.6 & T1.1, T1.2	Sh	(Sl.) stony	y(Br,O)/yBr	0 → 120	Q, F, D - I, C	SL 18	1.1	5.1 / 5.5	8	Outcrops, slope, (soil thickness), SOM, pH, CEC						
		E. head	Concave	20 - 50		Crops on sloping terraces (aband. terraces)	Augerings L1.5, L1.6	Sd - (Sh)	(Sl.) stony	Br/Br,brBl	50 → 120	Q, F, [D] - I, C	SL 14 / 18	1.6 / 2.2	6.3 / 5.9	16 / 19	(Slope), (soil thickness), (SOM), (pH)	2.1 → 2.5	1.1 - 2.3	5.6 - 7.8	0.19 - 0.43	1.8 - 4.7	1.4 - 1.8
	Dolomite Shale	W. side & head	Convex, Linear Linear, Concave	15 - 25 35 - 60		Outcrops, pine tree Crops on sloping terraces	Augerings T1.7, T1.6, T1.8 Profile P2	(Sh) - (D)	(Sl. Stony)	yO/yBr-rBr	0 → 120	Q, F, (H) - C, I	SL - SCL / SL - SC 10 - 31 / 15 - 24 - 50	0.4 - 1.2	5.5 - 5.9	5 - 15 / 6 - 20 - 28	Outcrops, Slope, (stoniness), (soil thickness), SOM, pH,	4.1→ 4.4	0.8 - 1.2	4.9 - 5.6	0.15 - 0.30	0.9 - 5.0	1.5 - 1.6
	Dolomite	Shoulder & sides	Convex, Linear	15 - 70		Outcrops, pine tree, mixed forest, (bush, crops on sloping terraces)	Augerings L2.8, L2.9 Profiles WP2, P3	(Sh) - D	Sl. stony	(r)Br/(d)rBr	0 → 120	Q, F, H - I, C	SL - SCL 12 - 23 / 25 - 37	0.7- 3.3 / ... 0.8	6.3 - 7.5 / ~ 6.2	13 - 18 / 15 - 21	Outcrops, (slope), (soil thickness), (SOM)…						
		Floor		10 - 15		Crops on sloping terraces & on terraces	Augerings L1.10 → L1.13	Sd - (Sh)	Sl. stony	(y)Br/(dBr)(brBl)	> 120	Q, F - I, C	SL 14 / 18	1.0 - 1.2	6.3 - 7.1	9 / 15	(SOM), (CEC)	3.1 → 3.3	1.2 - 1.4	6.4 - 7.7	0.19 - 0.28	1.4 - 3.0	1.0 - 2.0
Middle Catchment Sector	Sandstone Shale - Dolomite contact	E. divide & side	Convex, Linear	10 - 50		Outcrops, mixed forest, grass	Augerings L2.10 → L2.12	Sh	Stony	yO/y(O,Br)	0 → 80						Outcrops, (slope), stoniness, (soil thickness)...						
				15 - 30		Outcrops, (Mixed forest), crops on sloping terraces	Augerings L2.13, L2.14, L2.16 Profile WP3	Sh - (Sd) - (D)	Stony	O,(y)Br/Br,drBr	0 → 120	Q, [F, H] - I, C, K	SL 16 - 19 / 25	0.6 - 1.6	5.0 / 5.4	7 -15 / 18	Outcrops, stoniness, (soil thickness), (SOM), pH, (CEC)						
		E. interfluve	Linear	15		Crops on sloping terraces	Augerings L2.17 → L2.20 Profile P4	Sh - (Sd) - (D)	Stony	Br/(d)(r)Br	> 100	Q, F, H - I, C, K, G	L - SL / L - SCL 18 - 21 / 26 - 30	1.4 - 2.3 /... 1.3	5.0 / 6.0	12 - 21 / 12 - 34	Stoniness, pH	8.1, 9.1 → 9.3	1.3 - 1.9	5.0 - 5.6	0.47 - 0.60	0.8 - 1.4	0.6 - 1.5
	Dolomite	E. shoulder	Convex, Linear	20		Outcrops, crops on sloping terraces	Augerings T2.6, T2.7 Profiles WP4 & P5	D - (Sh) - (Sd)	Stony	(d)(r)Br/(d)rBr	0 → 120	Q, F, H - C, I, K, G	L - SL / SCL - SC 20 - 25 / 29 - 40	1.1 - 1.3 / 0.8	6.7 - 7.8 / 6.1 - 7.1	13 / 18	Outcrops, stoniness, (soil thickness), SOM	8.2, 8.3	1.1 - 1.5	6.8 - 7.7	0.31 - 0.36	1.1 - 1.2	
		Sides	Convex, Linear	30 - 80		Outcrops, bush, crops on sloping terraces	Augering T2.5 (1hor.)	D	Stony	rBr	0 → 40	Q, [F], D, [H] - C, I, K, G	SL 20	5.6	7.3	13	Outcrops, slope, stoniness, … soil thickness…						
		Floor		15 - 25		Crops on sloping terraces & on terraces	Augerings L1.14 → L1.17	D - Sd	Sl. stony	(r)Br/dBr	> 100	Q, F, D, [Ca, H] - I, C, K, G	SL 15 - 25 / 17 - 22	1.8 / 1.5	7.3 / 7.6	17 - 23 / 19 - 21	(pH)	7.1 → 7.3	1.5 - 1.7	5.7 - 8.0	0.19 - 0.27	2.8 - 4.8	1.8 - 2.1
	Shale	W. divide (& side)	Convex, Linear	15		Outcrops, [bush], Crops on sloping terraces	Profile WP1 T2.1 → T2.3	Sh	(Sl.) stony	yBr	0 → 120	Q, F, H - S, C, I, K	SL 20 / 27	0.4	4.7 / 5.5	33 / 36	Outcrops, (stoniness), (soil thickness)…SOM, pH						
Lower Catchment Sector	Shale	Divides & sides	Convex, Linear	20 - 40 50 - 70		Outcrops, ... crops on sloping terraces	Augerings L2.22 & L2.23	Sh…Sd - D	Stony	(y)Br	0 → 20						Outcrops, slope, stoniness, ...soil thickness, (SOM), (pH)	11.1, 12.1, 12.2 11.2, 11.3, 12.3	1.2 - 1.7 1.1 - 2.1	7.3 - 8.0 5.6 - 6.1	0.37 - 0.40 0.55 - 0.72	0.9 - 2.1 0.5 - 2.3	1.2 - 1.9 0.2 - 1.5
		Outlet		10 - 20		Crops on terraces	Augerings L1.26, L1.27 Profile P6	Sh - D - Sd	(Sl.) stony	yO/Y	40 → 120	Q, F, D, [Ca] - I, C, [K], G	L - SL 11 - 20 / 13 - 20	1.6 - 2.3 / ... 0.9	6.9 - 8.0 / 8.2	13 - 21 / 13 - 16	(soil thickness)	10.1 → 10.3	1.7 - 2.8	6.5 - 8.0	0.43 - 1.17	6.8 - 13.1	1.3 - 2.4

Note:	Position	Soil stoniness	Soil colour		Mineralogy for underlined augerings only			Soil Texture	Others	
	E. : Eastern	Sd : Sandstone	O : orange	y :yellowish	Q : Quartz	H : Hematite	K : Kaolinite	L : Loam	CEC : Cation Exchange Capacity at pH7	TOC : Total Organic Carbon
	W. : Western	Sh : Shale	Y : yellow	br : brownish	F : Fedspar	I : Illite	G : Gibbsite	SL : Silt loam	SOM : Soil Organic Matter	Avail. : available
		D : Dolostone	Br : brown	r : reddish	Ca : Calcite	C : Chlorite	( ) : locally	SCL : Silty clay loam	- : minimum-maximum	8 < C/N < 15 for composite samples
		Sl : Slightly	Bl : black	d : dark	D : Dolomite	S : Smectite	[ ] : traces	SC : Silty clay	/ : at surface /at depth	

compared with SR2, US2, US3, US5, MS2 and MS3. Geounits on the narrow alluvial plain, US2, US5 and MS6, have relatively high total exch. cation contents, compared to their adjacent units on the interfluves. More details of soil fertility evaluation are presented in Section 3.4.

Figure 3.2.24. An example illustrating the links between geomorphopedological units, reference plots and soil analytical data.

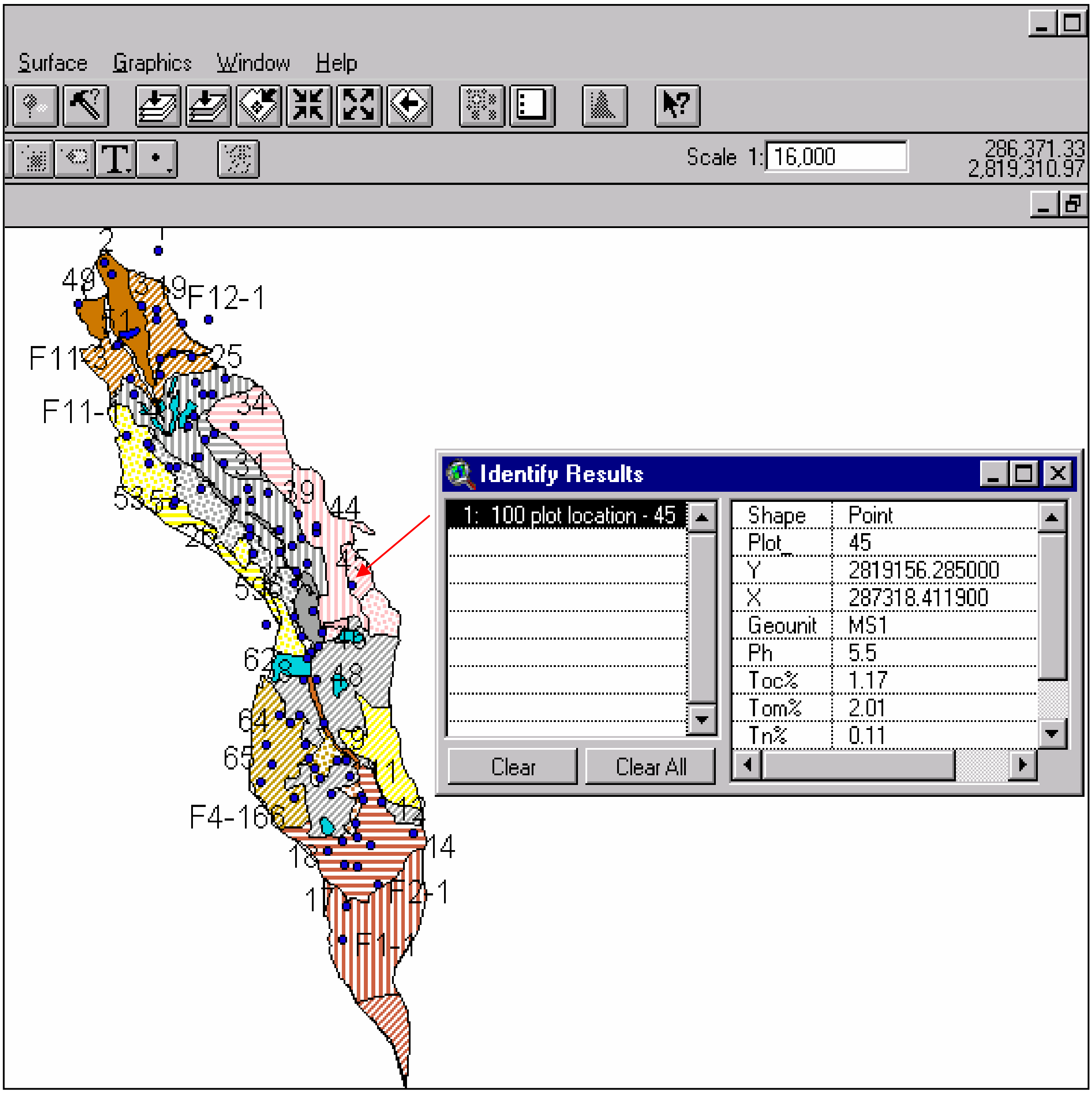


Table 3.2.16. Soil fertility parameters for different geomorphopedological units (to be continued)

Geounit	N	pH				Organic C %				Organic N %				Ca^{++}meq/100g				Mg^{++}meq/100g				K^{+}meq/100g				Total exch. cation meq/100g			
		Min.	Mean	Max.	StDev	Min.	Mean	Max.	StDev	Min.	Mean	Max.	StDev	Min.	Mean	Max.	StDev	Min.	Mean	Max.	StDev	Min.	Mean	Max.	StDev	Min.	Mean	Max.	StDev
LS1	4	5,7	6,8	8,0	1,1	1,10	1,43	2,10	0,46	0,09	0,13	0,17	0,04	3,0	31,7	95,5	43,5	1,60	3,54	5,81	2,19	0,37	0,52	0,72	0,17	5,2	35,8	101,7	45,2
LS2	3	6,5	7,2	7,7	0,6	1,70	1,83	1,90	0,12	0,15	0,16	0,17	0,01	7,6	27,4	62,6	30,6	1,85	2,85	4,11	1,15	0,43	0,52	0,58	0,08	10,0	30,7	67,3	31,7
MS2	2	5,0	5,2	5,3	0,2	1,30	1,35	1,40	0,07	0,11	0,13	0,14	0,02	3,2	3,5	3,8	0,4	1,09	1,33	1,56	0,33	0,50	0,55	0,59	0,06	4,8	5,3	5,9	0,8
MS3	1	5,6	5,6	5,6	*	1,90	1,90	1,90	*	0,14	0,14	0,14	*	5,4	5,4	5,4	*	2,01	2,01	2,01	*	0,47	0,47	0,47	*	7,9	7,9	7,9	*
MS4	2	5,5	6,2	6,8	0,9	1,50	1,60	1,70	0,14	0,12	0,13	0,13	0,01	6,0	21,1	36,1	21,2	2,11	2,81	3,51	0,99	0,36	0,48	0,60	0,17	8,7	24,3	39,9	22,1
MS5	3	5,6	7,0	7,8	1,2	1,10	1,50	1,70	0,35	0,10	0,13	0,15	0,03	4,4	13,9	19,8	8,3	1,88	8,43	13,31	5,90	0,31	0,41	0,55	0,12	6,9	22,8	31,2	13,8
MS6	3	5,7	6,9	8,0	1,2	1,50	1,60	1,70	0,10	0,13	0,14	0,16	0,02	28,3	46,7	57,4	16,0	2,02	3,12	4,26	1,12	0,19	0,23	0,27	0,04	30,5	50,1	61,9	17,1
SR2	2	5,5	5,8	6,0	0,4	1,30	1,60	1,90	0,42	0,11	0,13	0,15	0,03	3,0	4,5	6,1	2,2	1,77	2,04	2,30	0,38	0,26	0,39	0,52	0,18	5,8	7,0	8,1	1,7
US2	3	5,6	6,5	7,8	1,2	1,10	1,67	2,30	0,60	0,13	0,15	0,20	0,04	6,3	11,0	18,5	6,6	2,34	4,53	8,66	3,58	0,19	0,20	0,21	0,01	9,1	15,7	27,4	10,1
US3	4	4,9	5,4	5,6	0,3	0,80	0,98	1,20	0,17	0,08	0,10	0,11	0,01	1,4	2,4	3,4	0,8	0,66	1,24	2,03	0,57	0,15	0,23	0,30	0,06	2,2	3,9	5,7	1,4
US5	3	6,4	7,1	7,7	0,7	1,20	1,30	1,40	0,10	0,12	0,14	0,15	0,02	6,5	7,7	8,8	1,2	1,36	2,19	2,66	0,72	0,19	0,24	0,28	0,05	8,1	10,1	11,6	1,8

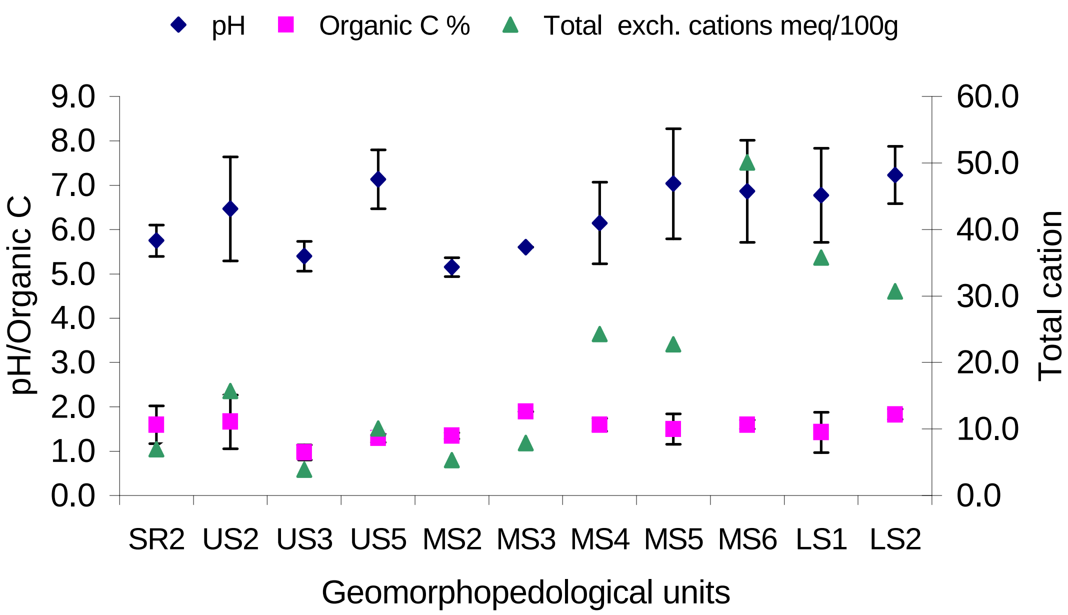
N = Number of soil samples in each geounit.

Table 3.2.16. Soil fertility parameters for different geomorphopedological units (continue from previous page)

Geounit	N	Available P mg/100g				Ex. Mn mg/ 100g				Ex. Zn mg/ 100g				Ex. Acidity meq/100g				Ex. Al^{+++} meq/100g				$CaCO_3$%				Maize yield kg/ha			
		Min.	Mean	Max.	StDev	Min.	Mean	Max.	StDev	Min.	Mean	Max.	StDev	Min.	Mean	Max.	StDev	Min.	Mean	Max.	StDev	Min.	Mean	Max.	StDev	Min.	Mean	Max.	StDev
LS1	4	0,50	1,15	2,10	0,68	30,0	190,8	445,2	178,1	1,00	1,28	1,60	0,28	0,18	0,31	0,45	0,19	0,03	0,10	0,18	0,11	3,34	3,34	3,34	*	*	*	*	*
LS2	3	7,00	10,90	13,10	3,39	169,0	286,0	426,0	130,0	2,40	3,77	4,70	1,21	0,15	0,15	0,15	*	0,03	0,03	0,03	*	1,66	1,66	1,66	*	3140	4290	5440	1626
MS2	2	1,20	1,30	1,40	0,14	41,0	74,5	108,0	47,4	0,80	0,85	0,90	0,07	1,80	0,48	1,14	0,94	0,40	0,80	1,20	0,57	*	*	*	*	5053	5053	5053	*
MS3	1	0,80	0,80	0,80	*	139,9	139,9	139,9	*	1,40	1,40	1,40	*	0,30	0,30	0,30	*	0,10	0,10	0,10	*	*	*	*	*	*	*	*	*
MS4	2	0,90	1,00	1,10	0,14	100,2	196,5	292,7	136,1	1,10	1,10	1,10	0,00	0,35	0,35	0,35	*	0,28	0,28	0,28	*	*	*	*	*	2500	3590	4680	1541
MS5	3	0,90	1,47	2,30	0,74	96,0	375,0	696,0	302,0	1,20	1,53	1,90	0,35	0,23	0,23	0,23	*	0,03	0,03	0,03	*	3,84	3,90	3,96	0,09	4680	6096	7667	1500
MS6	3	2,80	3,47	4,80	1,16	317,7	357,9	429,0	61,7	2,10	2,20	2,30	0,10	0,15	0,15	0,15	*	0,10	0,10	0,10	*	1,05	1,05	1,05	*	7180	7793	8260	555
SR2	2	2,10	2,10	2,10	0,00	60,2	88,2	116,2	39,6	0,90	1,05	1,20	0,21	1,40	0,50	0,95	0,64	0,30	0,75	1,20	0,64	*	*	*	*	*	*	*	*
US2	3	1,80	3,13	4,20	1,22	82,0	287,0	571,0	254,0	0,80	1,63	2,50	0,85	0,38	0,35	0,36	0,02	0,08	0,10	0,13	0,04	4,14	4,14	4,14	*	5460	6480	7080	888
US3	4	0,90	2,33	5,00	1,87	22,8	81,4	163,9	61,5	0,50	0,73	0,90	0,17	1,75	0,25	0,76	0,70	0,10	0,46	1,10	0,44	*	*	*	*	5840	6153	6580	383
US5	3	1,40	2,07	3,00	0,83	169,1	200,1	237,1	34,4	1,30	1,87	2,40	0,55	0,20	0,20	0,20	*	0,03	0,03	0,03	*	0,20	0,20	0,20	*	4080	5680	7840	1942

Note: Data population for exchangeable acidity and Al^{+++}, $CaCO_3$ and yield are different from other items.

Figure 3.2.25. Selected soil parameters for selected geomorphopedological units (error bar denotes standard deviation).



3.3. Agrosystem assessment.

Improved technologies have to fit into local agricultural reality. To assess crop production and to analyse effects of different agricultural practices, 100 plots were selected as reference plots in Wang Jia Catchment. These were farmers' plots and were cultivated by farmers themselves. This approach allows information collected from real agricultural systems, encourages farmers' involvement and helps to understand farmers' perception and adoption of recommended technologies. However, available statistical analysis approaches for data collected under such uncontrolled conditions are limited. Both field measurement data and data from farmers' survey cards about the 100 plots are analysed and presented in this section.

3.3.1. Field measurements of maize productivity in the catchment.

3.3.1.1 Comparison of maize yields by year

The average yields from the surveyed plots over four years are shown in Table 3.3.1. In 1999, maize in some lower plots was harvested by farmers before yield was measured due to early crop maturity, consequently only 81 out of 100 plots were surveyed. Based on these data, mean yield was 5401 kg/ha with a standard deviation of 1563 kg/ha and most fell into 3750-7250 kg/ha. The minimum yield of 1920 kg/ha was measured in plot No. 10. This plot was located in geomorphopedological unit US4 with a plant density of only 27,247 plants/ha for variety HD4. This plant density was only one-third of the optimum (75,000-82,500 plants/ha for HD4) recommended for high yields. The maximum yield of 9040 kg/ha was obtained in plot No. 23, which was located in MS4 with a plant density of 72819 plants/ha for Q3 (an old variety). Differences in plant density appeared to make a big contribution to the variation in maize yield throughout the catchment.

Table 3.3.1. Maize yields in 1999-2002 (kg/ha at 13% moisture content).

Year	N of plots	Mean	StDev	Minimum	Maximum
1999	81	5401	1563	1920	9040
2000	83	4954	1563	1608	8444
2001	76	4410	1485	909	9293
2002	96	6165	1452	3511	10547

In 2000, 83 plots were surveyed, with a mean yield of 4954 kg/ha and a standard deviation of 1563 kg/ha (Table 3.3.1). Most of the plot yields were between 2750-7250 kg/ha. The minimum yield of 1608 kg/ha was measured in plot No. 35 which was located in geomorphopedological unit MS5 with a plant space of 70 cm and row space of 40 cm for HD4. The maximum yield of 8444 kg/ha was obtained in plot F10-2 which was located in LS2 with a plant space of 52.5 cm and row space of 43.4 cm for DF4. Besides, plot No. 35 had a slope of 19.3° facing WSW at 2005 m asl, while F10-2 had a slope of 5° facing NNW at 1929 m asl.

In 2001, 76 plots were surveyed, with a mean yield of 4410 kg/ha and a standard deviation of 1485 kg/ha (Table 3.3.1). Most of plot yields were between 3500-6500 kg/ha. The minimum yield of 909 kg/ha was measured in plot No. 66 which was located in US3 with a slope of 27.3° at 2146 m asl. The maximum yield of 9293 kg/ha was obtained in plot No. 50 which was located in LS1 with a slope of 19.0° at 1992 m asl.

In 2002, 96 plots were surveyed, with a mean yield of 6165 kg/ha and a standard deviation of 1452 kg/ha (Table 3.3.1). Most of plot yields were between 3250-8250 kg/ha. The minimum yield of 3511 kg/ha was measured in plot No. 51, which was located in unit LS1 with a slope degree of 22.5° facing NNE. The maximum yield of 10547 kg/ha was obtained in plot No. 50, which was located in LS1 with a slope degree of 19.0° facing ENE.

The mean yields for each of the four years were higher than the mean yield of Yunnan Province in 2000, which was 4194 kg/ha according to China Maize Production (2003). However, they were much lower than the yields harvested in the experimental plots with modified/innovative practices at the same time in the same catchment (Wang, 2003). This indicates a considerable potential to increase maize yield with these modified/innovative practices in the catchment. There were big differences in mean yields between different years. Generally, 2002>1999>2000>2001. Since the data population was different and the available data were not exactly from the same plots for different years, paired-T tests were used to test the significance. The results showed significant differences between any two years of 1999-2002 (Table 3.3.2). These differences may be due to many factors, including meteorological factors, crop practices and seed variety and quality. Total rainfall was high in 1999, but low in 2000 (Figure 3.2.1). The seed germination was not good in 2000. In 2001, more rain fell in the crop early stage. Unfortunately, an unexpected heavy hail storm (09 August) influenced final yields considerably. In 2002, farmers were subsidized for using improved crop techniques with strong influence from local government. The detailed analyses of cultivar and crop techniques were presented later in this chapter.

Table 3.3.2 Paired T-Test of maize yields in 1999 to 2002 (kg/ha).

Comparison	N	Mean	StDev	SE Mean	T-Value	P-Value
2002-2001 Difference	75	1846	1668	193	9.59	<0.001
2002-2000 Difference	82	1207	2079	230	5.26	<0.001
2002-1999 Difference	78	639	1786	202	3.16	<0.01
2001-2000 Difference	70	-505	1640	196	-2.58	<0.01
2001-1999 Difference	66	-1000	1808	223	-4.49	<0.001
2000-1999 Difference	70	-505	1694	202	-2.49	<0.05

3.3.1.2 Comparison of maize yield by location

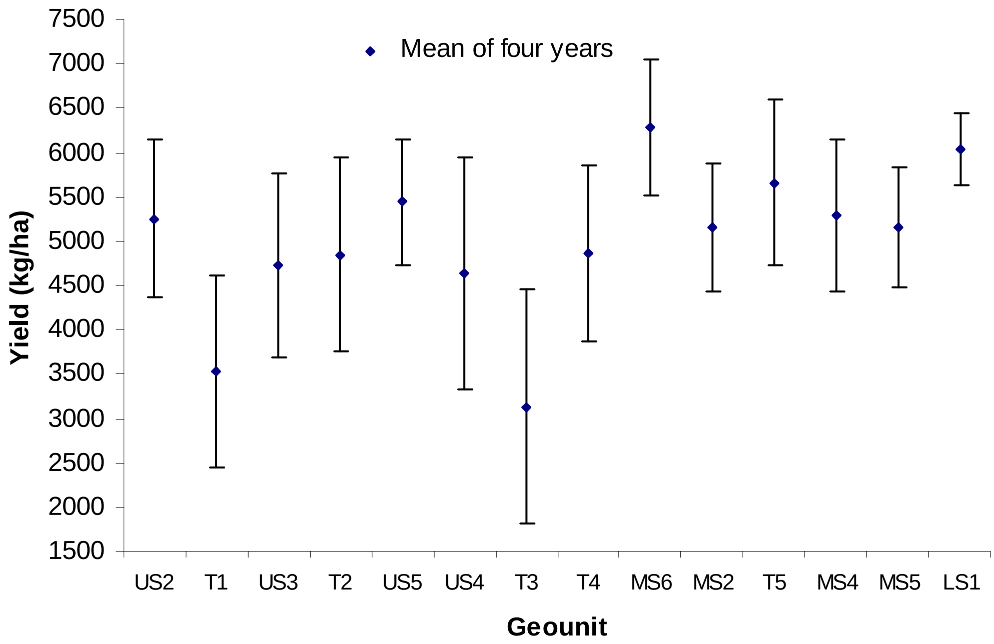
Among the 16 geomorphopedological units and 5 transitional units, some 16 units were involved in the 100 plot study. Among the missing units, SR1 and SR2 are under mixed forest with sandstone outcrops or abandoned terraces due to low temperature. US1 and MS1 are also under forest with outcrops, while MS7 is a unit with small area used for crop production. The general comparison of maize yield produced in different units is shown in Table 3.3.3. Data for different years were sorted in the order of mean from

Table 3.3.3. Maize yield for different geomorphopedological units.

1999						2000						2001						2002					
Geounit	N	Min.	Max.	Mean	StDev	Geounit	N	Min.	Max.	Mean	StDev	Geounit	N	Min.	Max.	Mean	StDev	Geounit	N	Min.	Max.	Mean	StDev
US4	4	1920	3920	3271	940	T3	1	2910	2910	2910	*	T3	1	1361	1361	1361	*	T3	1	4247	4247	4247	*
T1	1	3800	3800	3800	*	T1	1	2974	2974	2974	*	T1	1	2417	2417	2417	*	T1	1	4926	4926	4926	*
T3	1	4020	4020	4020	*	T4	1	3509	3509	3509	*	US3	8	909	5464	3434	1759	US3	8	3683	6240	5137	941
MS4	4	2800	6120	4411	1357	US3	8	2989	6229	4455	1121	T2	2	2752	4135	3444	978	T2	2	5388	5465	5427	54
MS5	20	2360	9040	5218	1909	US2	11	1780	6882	4457	1677	US4	2	1555	5953	3754	3110	T4	2	5633	5942	5788	218
T4	2	5320	5400	5360	56,6	T2	2	3373	5731	4552	1667	MS2	6	1763	6884	4359	1808	US4	2	4959	6846	5903	1334
MS2	6	2500	7880	5381	1763	MS5	18	1608	7739	4819	1665	MS5	18	2828	5938	4512	866	US5	5	4775	6919	6028	842
LS2	2	5053	5800	5427	528	MS2	5	2525	6920	4861	1769	US2	10	1703	6794	4618	1492	MS2	6	4477	7923	6039	1295
T5	6	4040	7160	5447	1136	US5	5	3448	6470	4961	1266	US5	3	2811	5806	4702	1646	MS5	21	3658	9239	6061	1508
US2	10	4240	7360	5556	1162	MS4	4	3086	7854	5376	2408	T4	1	4752	4752	4752	*	LS2	5	4485	7841	6092	1502
LS1	5	4324	7667	5686	1531	T5	6	3841	6645	5377	982	T5	6	3695	5634	4829	784	US2	10	3942	8386	6380	1354
US3	5	4680	6580	5860	713	US4	2	5289	5910	5600	439	MS4	4	3936	6385	4953	1080	MS4	4	5808	7955	6433	1022
MS3	1	5940	5940	5940	*	MS6	6	4678	7568	5917	1027	MS6	5	3998	6334	5418	1085	LS1	11	3511	10547	6499	2011
T2	2	5900	6000	5950	70,7	LS1	6	5694	6889	6222	399	MS3	1	5680	5680	5680	*	MS6	6	5198	8114	6636	963
US5	5	4080	7840	6072	1673	LS2	2	6507	8444	7476	1370	LS1	4	3886	9293	5691	2456	MS3	1	6745	6745	6745	*
MS6	6	4960	8260	7160	1189	MS3	0	*	*	*	*	LS2	0	*	*	*	*	T5	6	3644	9979	6993	2450

lowest in the top to highest in the bottom of the column. Although the trend for four years is not consistent, T1, T3 and US3 normally had the lowest maize yield, while units MS6, LS1 and MS3 had relatively high maize yield. In the upper part, US2 and US5 normally had relatively good yields. One-way ANOVA (Analysis of Variance) of four year's yield mean versus geounit is shown in Figure 3.3.1. Among the different geounits, significant differences exist ($P<0.001$). The one-way ANOVA of altitude, slope degree and slope face at plot level did not shown any significant differences.

Figure 3.3.1 Mean yield of four years for different geomorphopedological units (error bar denotes the standard deviation).



Taking only upper, middle and lower sectors for comparison, the trend for maize yield was consistent over the four years. It was always the lower sector which had the highest yield, while the upper sector had the lowest yield (Table 3.3.4).

Table 3.3.4. Mean maize yield in different sectors of the catchment (kg/ha).

Sector	1999		2000		2001		2002		Mean
	N	Mean	N	Mean	N	Mean	N	Mean	
Lower	7	5612	8	6567	4	5691	16	6349	6055
Middle	27	5409	41	4996	42	4585	47	6219	5302
Upper	46	5334	29	4577	26	4022	28	5808	4935

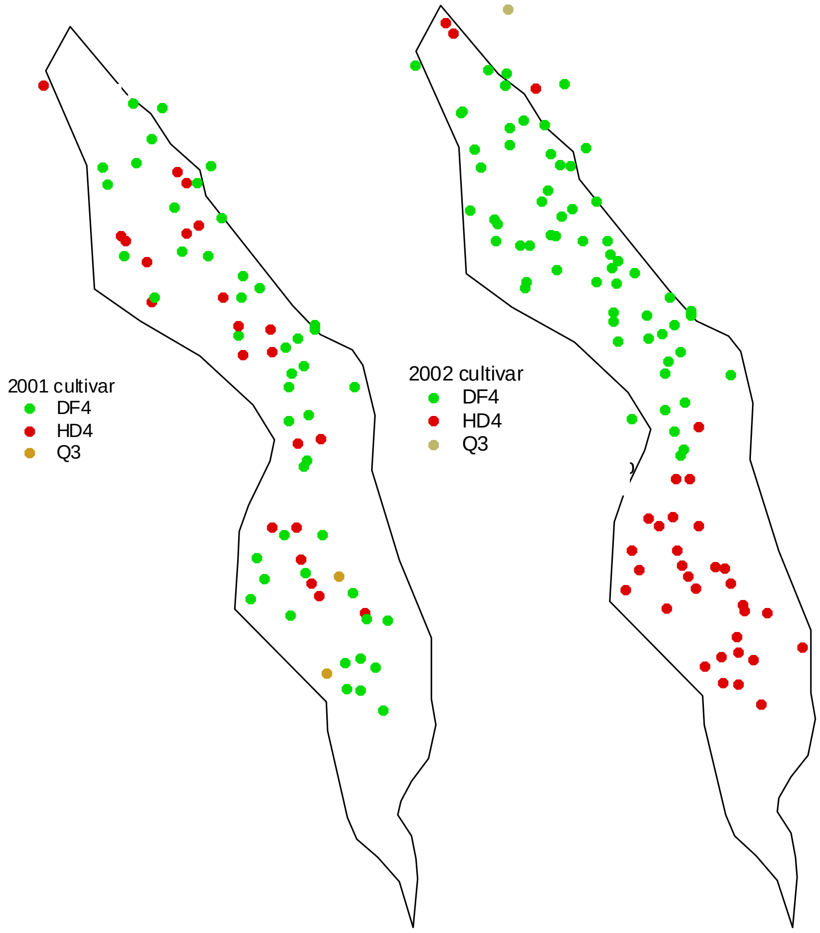
3.3.1.3 Comparison of maize yield by cultivar and plant density

There were 13 cultivars recorded in 1999, 11 in 2000, 4 in 2001 and 3 in 2002. In 1999 and 2000, some cultivars had only one or two observations (LD1, DH3, DH4, LD2, LD and YD). Only the main cultivars are presented in Table 3.3.5. Among the three main cultivars, Q3 is a relatively old cultivar with high yield but low quality and suitable only for animal feed. DF4 is a high yield cultivar and was introduced to the catchment in 2000. It has been adopted by increasing numbers of farmers since then. However, DF4 need relatively high soil fertility and temperature. During the field observations in 2000 and 2001, it was noticed that the poor maturity for DF4 occurred in the upper catchment due to insufficient cumulative temperature. This is also reflected in a low mean yield for DF4, compared to HD4 in 2000 and 2001, although the maximum yields of DF4 were higher than HD4, meaning DF4 has high yield potential. In 2002, when more attention was paid to cultivation techniques and DF4 was planted mostly in the lower and middle catchment, its mean yield surpassed HD4 (Figure 3.3.2). However, the one-way ANOVA of mean yields for each of the four years showed no significant difference (P = 0.540).

Table 3.3.5 Maize yield with different cultivars (kg/ha).

Variable	Cultivar	N	Mean	StDev	Minimum	Maximum
1999	-	27	5049	1247	3100	7667
	HD4	24	5315	1789	1920	8260
	Q3	30	5787	1590	2500	9040
2000	-	15	5073	1335	3086	6920
	DF4	29	4610	1759	1780	8444
	HD4	31	5215	1382	1608	7568
	Q3	8	4972	1922	2525	7854
2001	-	13	3891	1076	2092	5490
	DF4	42	4407	1739	909	9293
	HD4	19	4614	1012	2752	6385
	Q3	2	5934	180	5806	6061
2002	DF4	63	6301	1603	3511	10547
	HD4	32	5904	1103	3683	8386
	Q3	1	5978	-	5978	5978

Figure 3.3.2. Cultivar distribution in Wang Jia Catchment in 2001 and 2002.



Plant density was measured in the field in four years. However, the survey was incomplete in 1999 and 2000. In general, HD4 had a relatively stable plant density during the four years (Table 3.3.6). Its density was similar to DF4, i.e. 60,000 –70,000 plants/ha. This is slightly lower than the optimum plant density for HD4 for high yield, which is 75,000–82,500 plants/ha. Due to poor germination in 2000, DF4 had a relatively low plant density, compared to 2001 and 2002. This may be another reason for the relatively low yield in 2000. Optimum plant density for DF4 is ~60,000 plants/ha. Taking the catchment as a whole, most plant density was 50,000–90,000 plants/ha (Table 3.3.7). Due to the large StDev, it is hard to compare plant density with maize yield. Generally, plant densities of 60,000–80,000 plants/ha had a reasonable yield. However, there were differences in different years, which may be related to cultivar, climate and soil fertility.

Table 3.3.6. Effect of different cultivars on plant density (plants/ha).

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Year	Cultivar	N	Mean	StDev	Minimum	Maximum
1999	HD4	15	62767	18952	27249	99452
	Q3	22	61343	18952	27249	99452
2000	DF4	7	47788	9305	37726	62524
	HD4	6	65593	26114	40498	109302
2001	DF4	44	70114	18393	39383	135907
	HD4	21	70390	13692	51020	95960
	Q3	2	73566	41323	44346	102786
2002	DF4	63	66955	24506	30075	198052
	HD4	33	69339	15816	46332	107527
	Q3	1	105190	-	105190	105190

Table 3.3.7. Effect of plant density on maize yield (kg/ha).

Year	Density(plants/ha)	N	Mean	StDev	Minimum	Maximum
1999	<50000	10	4320	1322	1920	6000
	50000-59999	11	5529	1554	3140	7740
	60000-69999	10	5747	1459	3340	7940
	70000-79999	8	7512	1006	5660	9040
	80000-89999	3	5433	587	4760	5840
	90000-99999	3	6447	1595	4680	7780
2000	<50000	8	3827	1708	1780	6825
	50000-59999	3	3872	786	2974	4432
	60000-69999	3	4476	1545	3157	6175
	>70000	4	5552	431	5078	6101
2001	<50000	4	3709	1703	1763	5806
	50000-59999	15	4172	1588	909	6334
	60000-69999	20	4414	1733	1703	9293
	70000-79999	15	4331	1398	1568	6794
	80000-89999	11	4912	972	3500	6385
	90000-99999	5	5112	1299	3203	6152
	>1000000	4	4098	1971	1361	6061
2002	<50000	13	6209	1671	4477	9239
	50000-59999	24	5853	1385	3614	9979
	60000-69999	23	6063	1129	3683	7924
	70000-79999	19	6510	1419	3644	8386
	80000-89999	7	5653	1641	3511	7998
	90000-99999	6	7457	2170	4926	10547
	>100000	4	5804	704	4775	6355

3.3.1.4 Comparison of maize yield by cropping practices

Contour cultivation

Contour cultivation is one of the main techniques recommended to conserve soil and water in Wang Jia Catchment and the region. However, the effects of contour cultivation on erosion vary according to rainfall and slope (Milne, 2001). In the same catchment, Huang (2001) found contour cultivation significantly increases crop yields. Wang (2003) reported that contour cultivation improved crop growth and increased yield compared with downslope cultivation, but the difference was not significant. In this study, because so many factors are involved in maize production in terms of the whole catchment, maize yield did not show a strong increase with contour cultivation, except in the 2002 field survey where only one downslope plot recorded (Table 3.3.8).

Table 3.3.8. Effect of cultivation direction on maize yield (kg/ha).

Year	Cultivation	N	Mean	StDev	Minimum	Maximum
1999	Contour	45	4992	1603	1920	9040
	Downslope	36	5913	1367	2800	8260
2000	Contour	27	4556	1787	1780	8444
	Downslope	53	5131	1442	1608	7739
2001	Contour	38	4030	1374	909	6385
	Downslope	35	4769	1524	1555	9293
2002	Contour	95	6167	1460	3511	10547
	Downslope	1	5978	-	5978	5978

The annual values for maximum yield showed that contour cultivation had high yield potential. But the minimum yields also occurred with contour cultivationin 1999, 2001 and 2002, so yields contour cultivation were very variable. However, the one-way ANOVA of yearly mean for the four years showed the difference is not significant (P = 0.383). Besides the effect of contour cultivation, one possible reason may be the complexity of the slope shape in the catchment. It was very often that part of the plot was cultivated along contour lines while the other part was not.

Polythene mulch

Polythene mulch is a well-known technique to increase crop yield in China. In the same catchment, Huang (2001) and Wang (2003) found polythene mulch significantly increased maize yield. In this study, maize yield with polythene mulch was normally higher than without polythene mulch, except for 2001 when hail storms occurred in the late stage of maize growth (Table 3.3.9). However, one-way ANOVA of yearly mean for the four years shows the yield difference between polythene mulch and no polythene mulch is not significant under such uncontrolled conditions (P = 0.567).

Table 3.3.9. Maize yield with polythene mulch (kg/ha).

Year	Polythene mulch	N	Mean	StDev	Minimum	Maximum
1999	No	68	5338	1618	1920	9040
	Yes	13	5730	1240	3619	7880
2000	No	74	4893	1574	1608	8444
	Yes	9	5459	1456	2989	7014
2001	No	69	4455	1509	909	9293
	Yes	7	3969	1221	2061	5639
2002	No	17	5458	1014	3644	7181
	Yes	79	6318	1492	3511	10547

3.3.2. Information from farmers' survey cards.

3.3.2.1 Comparison of maize yield by cropping direction and polythene mulch.

Farmers have been working in Wang Jia Catchment for many years and have their own opinions about their land and crop. It is crucial to understand farmers' opinions about their cropping practices. However, the information from farmers' survey cards was not very accurate. Farmers estimated their maize yields based on field baskets. According to the farmers' survey card, maize mean yield in 2002 was greatly increased, compared to 2001 (Table 3.3.10), by ~ 1765 kg/ha. This result means the farmers can recognized the increase of maize yield in 2002. This increase can be partly explained by the increase in use of polythene mulch in 2002. Some 85 out of 97 plots were polythene mulched in 2002, compared to 7 out of 93 plots in 2001. Maize yields with polythene mulch were higher than without polythene mulch in both two years. Contour cultivation did not show any advantage in increasing maize yield, compared to downslope cultivation.

Although the winter and early spring is very dry in the catchment, farmers seem not to use the irrigation system very much for maize production, especially in the wet year (2002) when the rainfall was good for crop establishment (Table 3.3.10). The reason for the low use of irrigation needs further study, especially from a socio-economic perspective.

Table 3.3.10. Maize information from farmers' survey card (kg/ha).

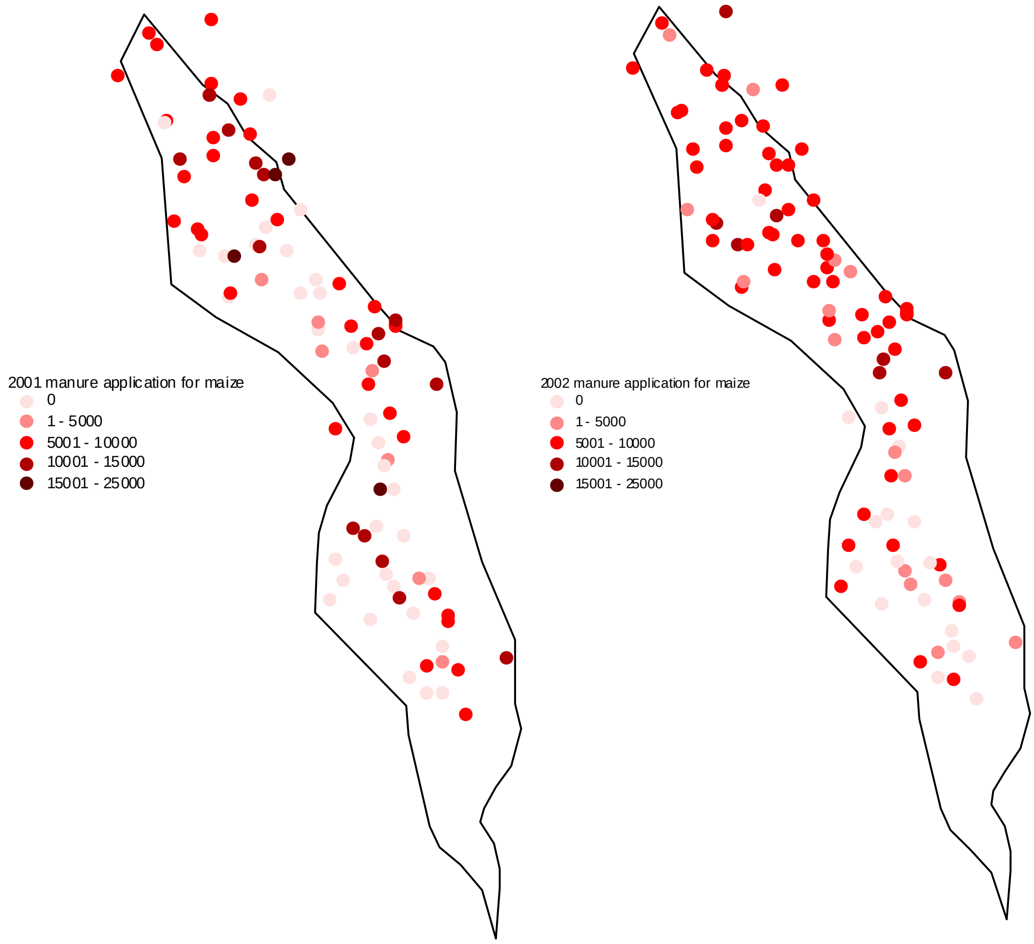
Year	Practice		N	Mean	StDev	Minimum	Maximum
2001	Irrigation	No	88	4114	1320	15	7000
		Yes	3	5267	1703	3300	6250
	Planting direction	Contour	84	4115	1351	15	7000
		Downslope	7	4596	1169	3000	6000
	Polythene mulch	No	84	4111	1347	15	7000
		Yes	7	4652	1209	3375	7000
	Total		91	4152	1338	15	7000
2002	Irrigation	No	96	5900	1049	1500	10500
		Yes	1	7500	-	7500	7500
	Planting direction	Contour	95	5899	1054	1500	10500
		Downslope	2	6750	1061	6000	7500
	Polythene mulch	No	12	5550	758	4500	7500
		Yes	85	5968	1085	1500	10500
	Total		97	5917	1056	1500	10500

3.3.2.2. Comparison of maize yield by manure and fertilizer application

The information on manure and fertilizer applications was collected via farmers' survey cards in 2001 and 2002. The distribution of manure applications shows that more plots were applied with manure in 2002 than in 2001 (Figure 3.3.3). Manure application was more concentrated in certain plots in 2001. The application rates in both years were typically lower than the rate recommended for high yield, which was 15,000 kg/ha. This may have been mainly due to the shortage of manure in the village. However, the higher manure application rates tended to be located in plots closer to the village in the middle and lower catchment, particularly in 2002. Therefore transport distance (the manure was carried up the catchment by back-pack) may also have been a factor.

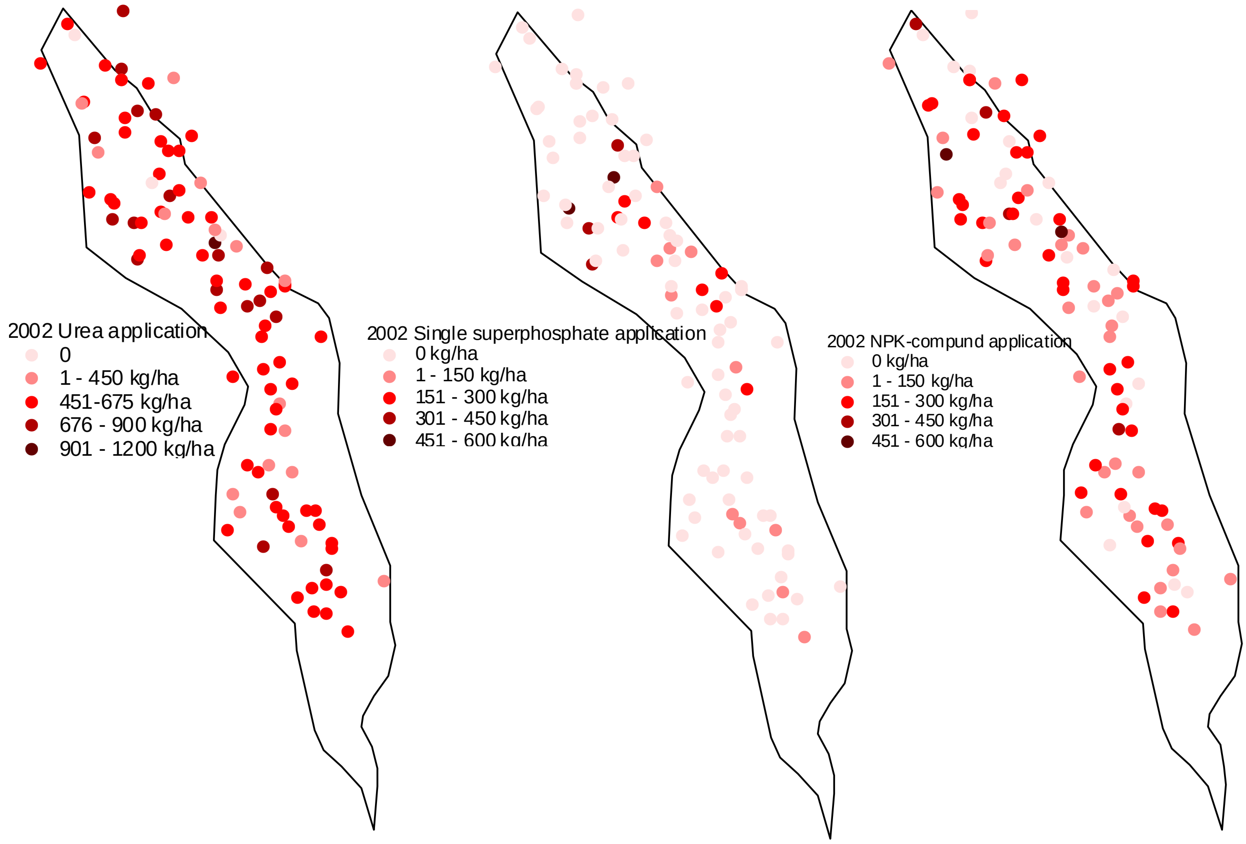
Figure 3.3.3. Distribution of manure applications in 2001 and 2002.

(Unit: kg/ha)



The chemical fertilizers used for maize production in the catchment were mainly urea as N fertilizer (only a few plots used ammonium bicarbonate), single superphosphate as P fertilizer and some NPK compounds (Figure 3.3.4). The farmers did not intentionally select the fertilizer variety. To some extent, the fertilizer used depended on what the farmers had available. The NPK compound was normally left over from tobacco production, with a N-P_2O_5- K_2O content of 15-15-15. In terms of number of plots, urea was the most common fertilizer, followed by NPK compound, then single superphosphate. Most plots were applied with urea at ~675 kg/ha, which was the recommended rate. Although the single phosphate rate applied was generally low compared to the recommended rate (300 kg/ha), the combination rate of single superphosphate and compound was ~300 kg/ha (the P_2O_5 content of single superphosphate is normally 16-20%). Like the manure, the application rate of fertilizers also had a relationship with the location in the catchment, especially the urea. Slightly more urea was applied in the lower and middle catchment.

Figure 3.3.4. Distribution of fertilizer applications for maize production in 2002.



Regression analysis of maize yield with manure, urea, compound and superphosphate application was conducted (Table 3.3.11). Due to the destructive effect of hail in 2001, only 2.4% of the variance of maize yield in 2001 are coupled with variability in manure and fertilizer applications. The P value of the regression equation is 0.712. However, analysis of the 2002 data showed that 21.8% of the variance of maize yield in 2002 was coupled with variability in manure plus fertilizer applications. The *P* value of the regression equation is <0.001. The further regression of maize yield with each single variable of manure, urea, compound and superphosphate application was conducted with the 2002 data. Among the manure and fertilizers, 14.9% of the variance of maize yield are coupled with variability in manure application (P<0.001); 10.7% are coupled with variability in urea application (P<0.001); while only 0.7% for NPK compound and none for single superphosphate with P values of 0.426 and 0.876, respectively.

Table 3.3.11. Regression analysis of maize yield with manure and fertilizer applications.

Year	Manure		Urea		Compound		Superphosphate	
	R^2(%)	P	R^2(%)	P	R^2(%)	P	R^2(%)	P
2001	0.1	0.729	1.7	0.214	0.5	0.522	0.1	0.806
2002	14.9	<0.001	10.7	<0.001	0.7	0.426	0.0	0.876

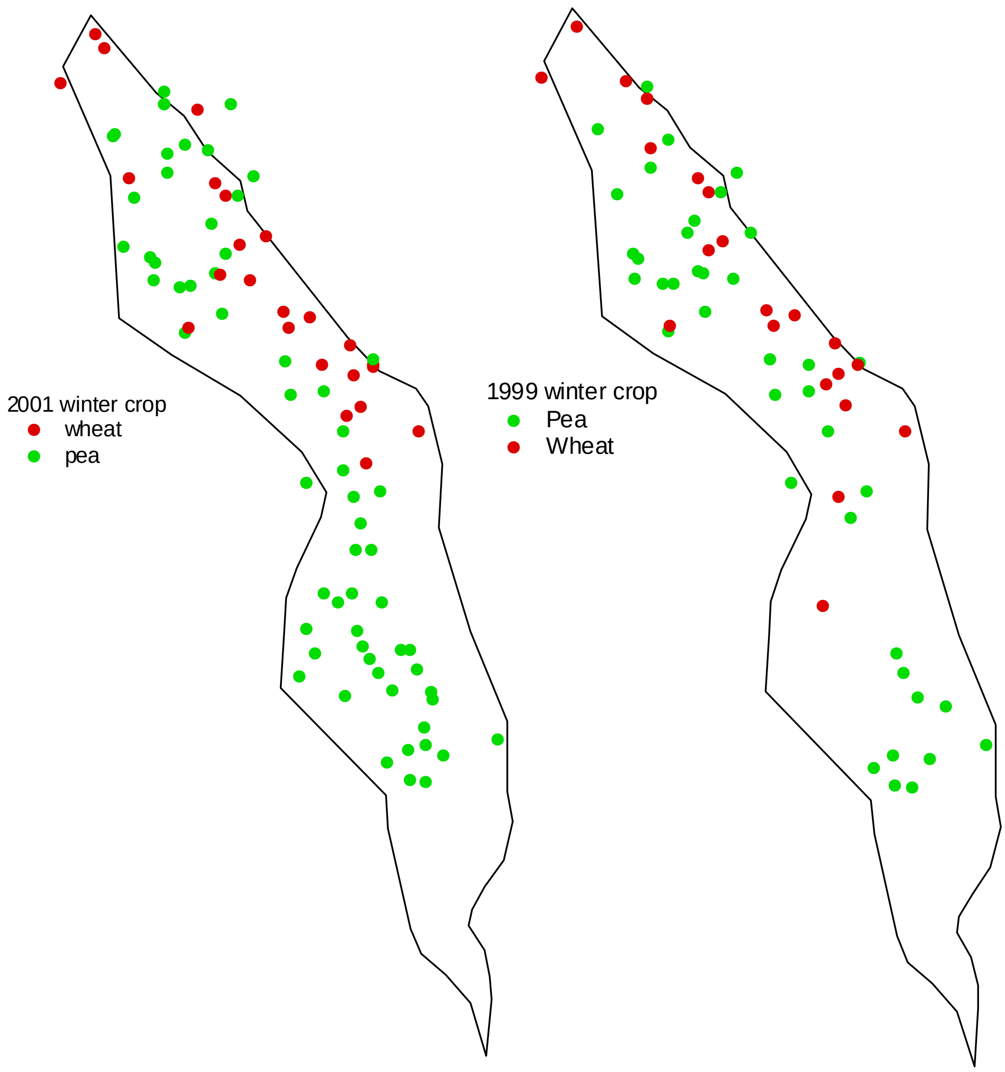
3.3.2.3. Winter crop information

Following the general agrosystem in this region, the main winter crops in Wang Jia catchment were wheat and pea (Table 3.3.12). In 2001, winter crop survey showed that 63 out of 97 plots were cultivated with garden peas and some farmers sold green peas for high prices. Only 31 out of 97 plots were cultivated with wheat. According to personal communications with these farmers, wheat was believed to deplete soil fertility. Normally wheat was planted in the plots close to the village, while pea was planted over all the catchment, especially in the upper part (Figure 3.3.5). Since the winter crop is not as important as summer crops to local farmers, the winter crop was cultivated extensively with relatively low yields, also due to the dry season. The minimum yields of both wheat and pea yielded straw, but no grain yield. The mean yield was 1013 and 671 kg/ha for wheat and pea, respectively. Most of the pea stalks were used as animal feed, as was some of the wheat straw. Only part of the wheat straw was left in the field (~34% in terms of plot number). With less planting area and low yield the wheat straw was insufficient for straw mulch in maize cultivation. In addition, some other factors, such as ploughing difficulty and labour consumption, contributed to the low adoption of straw mulch in maize production.

Table 3.3.12. Winter crop yield in 2001 (kg/ha).

Winter crop	N	Minimum	Maximum	Mean	StDev
2001 wheat	25	6	1800	1013	867
2001 pea	44	19	4125	671	523

Figure 3.3.5 The distribution of winter crops in 1999 and 2001



3.4. Soil fertility evaluation at catchment, geounit and plot levels.

Soil fertility is one of the main variables which determine crop yield. For soil fertility evaluation, analytical data from soil samples sets 2, 4, 5 and 7 were used (Table 2.4). These data were synthesized and analysed at catchment, geounit and plot level.

A mixed qualitative/quantitative evaluation methodology was employed. The qualitative evaluation was carried out by comparison of the catchment soil fertility parameters with the relevant thresholds used in China (Shi, 1988). The quantitative evaluation was more complicated. Firstly, principal component analysis was carried out to examine how many main components exist. Secondly, factor analysis was carried out to assign a weight for each soil fertility parameter. Finally, these weights was multiplied with the soil parameter data and summed up for each soil sample to give a soil fertility index.

3.4.1 Catchment level

Soil analytical data were analysed using basic descriptive statistics to give a general overview of soil fertility at catchment level. Data presented here for winter 1999 was from soil sample Set 4 (Table 3.4.1). In winter 1999, a wide $pH_{(H2O)}$ range of 5.2-8.0 was obtained. This suggests varied conditions within the catchment, which can be slightly acidic to neutral/calcic or carbonate-rich. This wide pH range reflects not only natural soil properties, but also the influence of human activities.

Table 3.4.1 General overview of soil fertility parameters in 1999

Parameter	Unit	N	Mean	StDev	Minimum	Q1*	Median	Q3*	Maximum
pH		97	6.37	0.78	5.20	5.60	6.40	7.05	8.00
Total organic matter	%	98	2.18	0.73	0.80	1.80	2.01	2.48	4.77
Total N	%	98	0.13	0.03	0.07	0.10	0.12	0.15	0.25
Available N	ppm	98	115.01	37.49	51.00	93.00	108.00	128.75	263.00
Available P	ppm	98	7.00	7.95	0.50	2.23	4.10	9.30	54.70
Available K	ppm	98	140.04	49.91	65.00	104.75	140.00	170.75	388.00

Note: Q1 = limit of lower quartile; Q3 = limit of upper quartile.

Some 75% of the soil pH data fell into the slightly acid to neutral category. Some 75% of soil organic matter contents were <2.5%, which is the low to middle level in China's standard, according to the analytical method employed (Shi, 1988). Only ~ 25% were at high levels and <25% low levels (total organic matter <1.0%). One quarter of total N content was at a high level (>0.15%), half the population had total N at the middle level (0.10 - 0.15%) and one quarter was at low level (<0.10%) (Shi, 1988). In terms of available N, >50% available N was at a high level (>100 ppm) and none of them was at low level (<50 ppm) (Shi, 1988). Some <25% available P was at a high level (>10 ppm), <25% at a middle level (5-10 ppm) and >50% at a low level (<5 ppm) (Shi, 1988). More than 50% of available K was at a high level (>125 ppm), >25% at a middle level (70-125 ppm) and only 1% at a low level (<70 ppm) (Shi, 1988). The regression analysis of total N (%) versus total organic matter (%) showed a significant relationship (r = 0.86, n = 98, P<0.001). Some 74.4% of variance of total N was coupled with the variability of total organic matter. The regression equation is:

Total N (%) = 0.0387 + 0.0400 total organic matter (%) 3(1)

This indicates the total nitrogen was mainly associated with organic matter. The relative low C/N suggested a favourable condition for organic matter mineralization.

The soil fertility parameters from soil samples Sets 5 and 7 are presented in Tables 3.4.2 and 3.4.3. These two sets of soil samples consisted of only the primary 30 plots. The general overview of these two data sets indicates the similar soil fertility situation as in Table 3.4.1, except for the relatively high soil available P level. There were two additional soil fertility parameters of total P and total K contents in Table 3.4.2. In terms of total P, >75% of the population was at slight to medium deficient level and none was at severely deficient level. None of them was at the severely deficient level for total K. Some 25-50% of the population had a fertile level of total K content (Zhang *et al.*, 1999).

Table 3.4.2. General overview of soil fertility parameters in 2001.

Parameter	Unit	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
pH		30	5.98	1.07	4.50	5.00	5.75	7.03	8.00
Total organic matter	%	30	2.57	0.62	1.23	2.08	2.59	3.07	3.82
Total N	%	30	0.15	0.04	0.09	0.12	0.15	0.17	0.29
Total P	%	30	0.07	0.03	0.03	0.05	0.07	0.09	0.14
Total K	%	30	2.78	0.89	1.13	2.27	2.56	3.66	4.64
Available N	ppm	30	89.80	26.67	50.00	64.75	93.00	107.25	156.00
Available P	ppm	30	20.57	8.86	8.00	15.50	19.00	24.25	43.00
Available K	ppm	30	128.67	44.50	66.00	93.50	124.50	158.50	268.00

Table 3.4.3. General overview of soil fertility parameters in 2002.

Parameter	Unit	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
pH		28	6.82	1.14	5.41	5.84	6.42	7.93	8.84
Total organic matter	%	28	2.64	0.57	1.40	2.24	2.65	3.17	3.99
Total N	%	28	0.15	0.03	0.08	0.13	0.15	0.19	0.25
Available N	ppm	28	93.93	34.78	43.00	65.00	88.00	113.75	185.00
Available P	ppm	28	22.04	12.18	1.30	11.23	20.50	31.83	47.90
Available K	ppm	28	136.07	47.73	77.00	93.25	130.00	162.50	276.00

A comparison of soil fertility parameters over three seasons was carried out using paired T tests (Table 3.4.4). The time period between the sampling dates in 2002 and 1999 was actually 2.5 years. This relatively short period of time was not expected to have real marked long term effects on soil fertility. However, significant changes were detected in some of the soil fertility parameters. Only available K showed non-significant change over the time period. These results suggest that the soil sampling may have been picking up short-term changes due to changes in cropping practice, especially manure and fertilizer application.

Table 3.4.4. Paired T-test of soil fertility parameters between 2002 and 2001 and 1999.

Comparison	Parameter	Unit	N	Mean	StDev	SE Mean	T-Value	P-Value
Difference of 2002 - 1999	pH		25	0.515	0.540	0.108	4.770	<0.001
	Total organic matter	%	25	0.731	0.282	0.056	12.980	<0.001
	Total N	%	25	0.021	0.018	0.004	5.770	<0.001
	Available N	ppm	25	-44.800	35.930	7.190	-6.240	<0.001
	Available P	ppm	25	14.180	9.320	1.860	7.600	<0.001
	Available K	ppm	25	4.680	44.530	8.910	0.530	0.604
Difference of 2002 - 2001	pH		28	0.76	0.72	0.14	5.59	<0.001
	Total organic matter	%	28	0.10	0.30	0.06	1.82	0.079
	Total N	%	28	0.00	0.04	0.01	0.52	0.604
	Available N	ppm	28	4.36	34.04	6.43	0.68	0.504
	Available P	ppm	28	1.71	10.35	1.96	0.88	0.389
	Available K	ppm	28	6.43	27.92	5.28	1.22	0.234
Difference of 2001 - 1999	pH		27	-0.319	0.523	0.101	-3.160	<0.01
	Total organic matter	%	27	0.501	0.574	0.110	4.540	<0.001
	Total N	%	27	0.015	0.039	0.008	1.950	0.062
	Available N	ppm	27	-53.480	34.370	6.610	-8.090	<0.001
	Available P	ppm	27	11.360	6.830	1.320	8.630	<0.001
	Available K	ppm	27	-2.370	47.150	9.070	-0.260	0.796

3.4.2 Geounit level

Soil pH

The analysis of 1999 soil data (soil sample Set 4) at geounit level is presented in Table 3.4.5. Geounits T4 and US3 on shale, SR2 on sandstone and T5, MS2 and MS3 on dolomite with influence of colluvium from shale or sandstone and shale had relatively low pH values (<6.0). LS2, MS6, US4 and US5 along the narrow alluvial plain, which had the direct influence of dolomite and strong influence of human cultivation, had relatively high pH values (>7.0). One way ANOVA showed significant differences among the geounits in terms of soil pH (P<0.01).

Total organic matter

Geounit SR2 under mixed forest had the highest total soil organic matter content of 4.03% due to non-cultivation. LS2 at the catchment outlet and closest to the village had the highest total organic matter content for cultivated soils, which was 3.37%, a high level according to the Chinese standard (>2.5%) and the analytical method employed. Then the second highest organic matter content was US5 at the upper alluvial plain with a total organic matter of 2.89%, followed by LS1, MS6, US2 and US4. The transition areas T2 and T4 had relatively low organic matter contents of <1.5%. These geounits all have a medium level of soil organic matter content, according to the Chinese standards (1-2.5%) (Shi, 1988). One way ANOVA showed significant differences among the geounits in term of total organic matter content (P < 0.001).

Total Nitrogen

Normally, a large proportion of soil total N is in the form of organic N. As reported before, total N had a close positive correlation with soil organic matter in the catchment. So averaged over geounit, soil total N content had a similar trend to soil organic matter. LS2 had both highest soil organic matter content and highest total nitrogen content in cultivated soil, followed by US5 and then SR2. Total N content of SR2 was not very high compared to its high organic matter content, which may have been due to the non-cultivation of this unit, with no applications of nitrogen fertilizer. LS2, US5 and SR2 had total N contents at a high level (>0.15%). while the transition areas T4 and T2 had relatively low total N contents (<0.10%). One way ANOVA showed significant differences among the geounits in term of total nitrogen content (P <0.001).

Table 3.4.5. Soil fertility parameters averaged from plots to geounits

Geo unit	N	pH		Total organic matter (%)		Total N (%)		Available N (ppm)		Available P (ppm)		Available K (ppm)	
		Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
LS1	11	6.24	0.61	2.44	0.59	0.14	0.02	133.2	17.9	9.56	5.68	163.3	43.7
LS2	5	7.42	0.54	3.37	0.99	0.20	0.04	167.4	58.1	28.02	16.77	225.4	92.7
MS2	6	5.78	0.64	1.88	0.21	0.11	0.01	112.2	33.8	7.52	8.25	171.3	52.3
MS3	1	5.60	-	1.97	-	0.13	-	145.0	-	2.00	-	162.0	-
MS4	4	6.70	0.22	1.91	0.22	0.11	0.01	76.5	11.1	1.40	1.61	140.0	27.0
MS5	21	6.41	0.71	1.98	0.40	0.11	0.02	106.6	17.1	2.97	2.96	138.5	45.3
MS6	6	7.20	0.24	2.34	0.28	0.14	0.02	125.5	49.5	8.03	6.69	109.5	21.4
SR2	2	5.50	0.14	4.03	0.97	0.16	0.01	157.0	67.9	18.85	3.04	129.5	44.6
T1	1	6.70	0.00	2.09	-	0.11	-	105.0	-	3.50	-	86.0	-
T2	2	6.55	0.50	1.36	0.19	0.09	0.02	58.5	10.6	2.55	2.90	90.5	23.3
T3	1	6.40	-	1.92	-	0.10	-	107.0	-	0.50	-	153.0	-
T4	2	5.30	0.14	1.49	0.01	0.08	0.01	98.0	5.7	3.05	0.64	181.0	17.0
T5	6	5.62	0.42	1.75	0.15	0.10	0.01	107.3	9.2	3.20	2.57	156.8	43.9
US2	10	6.02	0.68	2.33	0.63	0.14	0.01	126.4	53.4	8.32	4.81	114.7	41.1
US3	8	5.84	0.39	1.54	0.41	0.10	0.02	90.3	23.3	5.09	2.67	131.3	28.0
US4	4	7.28	0.46	2.19	0.50	0.12	0.03	102.5	17.1	3.18	2.18	113.5	35.6
US5	5	7.26	0.73	2.89	1.34	0.17	0.05	139.8	37.5	7.64	4.12	104.8	8.8

Available Nitrogen

Geounit LS2 had both the highest total N content and the highest available N content, followed by SR2, MS3, US5, LS1, US2 and MS6. This trend was exactly the same as for total N. All these units had high levels of available N content according to the Chinese standard (>100 ppm). Only the geounits MS4, T2, T4 and US3 had medium levels of available nitrogen content (50-100 ppm). One way ANOVA showed significant differences among the geounits in term of available N content (P <0.001).

Available Phosphorus

The geounits which were relatively fertile with gentler slopes and were likely to have been cultivated with more care, typically had high available P contents. Geounit LS2 had the highest total N, available N, available P and soil organic matter contents and relatively neutral pH. This was followed by SR2, LS1, MS6, US2, US5 and MS2. All these units had a very high level of available P content by the Chinese standard (>10 ppm). LS1, MS6, US2, US5, MS2 and US3 had a medium level of available P. MS3, MS4, MS5 T1, T2, T3, T4, T5 and US4 had low levels of available P content, especially the transition areas T1-T5. These suggest that soil P content may mainly relate to human activities, i.e manure and phosphorus fertilization in the catchment. One way ANOVA showed significant differences among the geounits in term of available P (P <0.001).

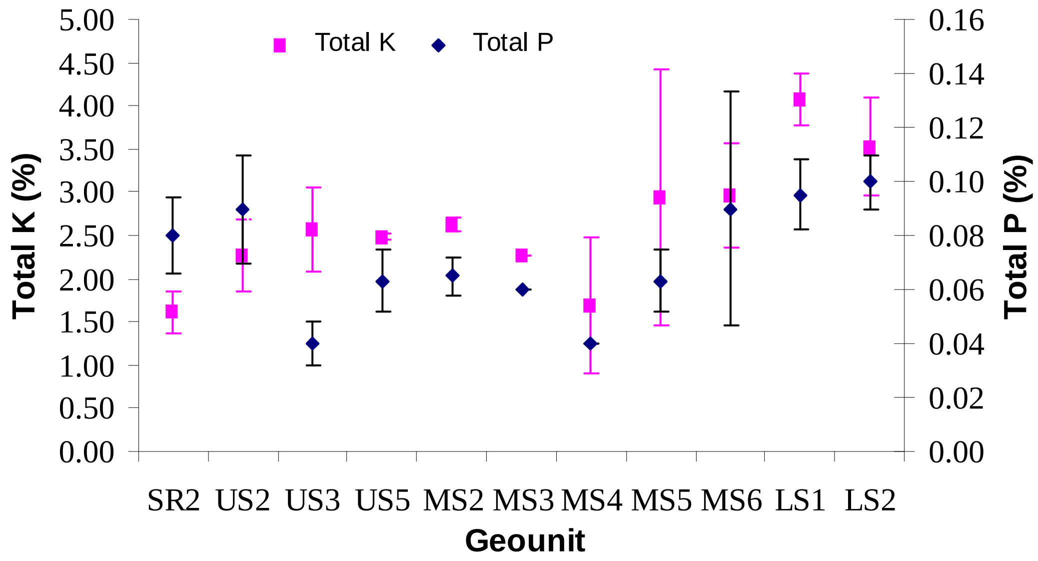
Available Potassium

Due to the mineralogy of the parent material, soil K content was expected to be influenced by the sandstone and shale in the catchment. Soil K content may also have been influenced by the history of tobacco cultivation in certain units, because of the high application rate of K fertilizer to tobacco. Organic matter or manure was also an important source of soil K. Geounit LS2 had the highest available K content, followed by T4, MS2, LS1, MS3, T5, T3, MS4, MS5, US3 and SR2. All these units had a high level of available K (>125 ppm) by the Chinese standard. The rest of the units had a medium level of available K. Due to topographic features, T1, T2 and US4 were not influenced by sandstone or shale, while remaining units were influenced by shale or sandstone either locally or as colluvial or alluvial materials. One way ANOVA showed significant differences among the geounits in term of available K content (P <0.01).

Total Phosphorus and Potassium

Additional parameters of total P and K were analysed from soil sample Set 5 and are presented in Figure 3.4.1. Since soil sample set 4 consisted only of the primary 30 plots, only 11 geounits were involved. Generally, LS1 and LS2 had high levels of total P (0.06-0.10%) and very high levels of total K (>3.0%) by the Chinese standard. MS6, US2, SR2, MS2, US5, MS5 and MS3 had high levels of total P (0.06-0.10%). MS4 and US3 had medium levels of total P (0.02-0.06%). MS6, MS5, MS2, US3, US5, MS3 and US2 had high levels of total K content (2.0-3.0%). MS4 and SR2 had medium levels of total K content (1.0-2.0%).

Figure 3.4.1. Soil total P and total K contents for different geounits (error bar denotes the standard deviation).



Other parameters

Additional parameters of exchangeable cations, exchangeable acidity and $CaCO_3$ content were analysed from soil sample Set 2 by GAU and are presented in Table 3.2.16 of Section 3.2.3.2. Since soil sample Set 2 consisted of 36 plots, only 11 geounits were involved. The presence of relatively high exchangeable Al in MS2, SR2 and US3 was related to relatively low pH of <6.0 and high exchangeable acidity. The presence of carbonates (in the fine-earth fraction) in LS1, LS2, MS5, MS6 and US5 was closely related to a relatively high pH of ~7.0. SR2, US3, MS2 and MS3 are the most acidic, with a pH <6.0, 0.10-0.80 meq/100g exchangeable aluminium, <6 meg/100g exchangeable calcium and <8.0 meq/100g total exchangeable cations. LS1, LS2, MS5, MS6 and US5 with pH ~7 have free carbonates, exchangeable calcium 7.7-46.7 meq/100g and total exchangeable cations 10.1-50.1 meq/100g.

Summary

The mean soil data from soil sample Sets 4, 5 and 7 showed similar results (Table 3.4.6). Generally, geounits in the flat or concave position (alluvial plain and catchment outlet) have relatively good soil fertility compared to the convex positions or steep slopes (the interfluves), due to parent materials, human activities and erosion. Meanwhile, geounits close to the village tend to have better fertility than those distant from the village.

Table 3.4.6. The mean soil fertility parameters of the primary 30 plots in 1999, 2001 and 2002.

Geo unit	N	pH		Total organic matter (%)		Total N		Available N		Available P		Available K	
		Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
LS1	12	6.37	0.73	2.35	0.44	0.16	0.05	115.17	37.19	14.17	9.09	133.00	48.33
LS2	9	7.15	0.96	3.19	0.51	0.19	0.04	128.22	39.78	27.48	10.80	149.56	48.70
MS2	6	5.29	0.24	2.20	0.50	0.13	0.02	101.67	41.32	21.35	15.64	182.00	53.01
MS3	3	5.80	0.35	2.74	0.67	0.15	0.02	110.67	35.56	17.87	20.94	177.00	15.52
MS4	4	5.45	0.37	2.17	0.09	0.12	0.01	73.25	15.37	11.53	2.87	131.00	16.15
MS5	8	7.08	0.72	2.21	0.37	0.14	0.02	99.88	18.86	10.93	7.63	124.00	25.81
MS6	9	7.46	0.64	2.74	0.47	0.16	0.02	120.22	40.54	18.01	9.20	101.56	21.08
SR2	4	5.20	0.39	3.49	1.10	0.15	0.03	125.00	60.98	21.43	7.39	122.25	48.29
US2	9	5.45	0.50	2.49	0.72	0.17	0.03	134.00	60.52	20.81	13.06	90.33	18.78
US3	12	5.85	0.57	1.78	0.52	0.11	0.02	76.25	27.65	11.74	7.54	120.75	32.16
US5	9	7.37	1.27	2.36	0.68	0.15	0.03	94.78	32.50	16.77	6.58	96.11	10.46
P* value		<0.001		<0.001		<0.001		<0.05		<0.05		<0.001	

* The P value of one way ANOVA of mean.

LS2 is the most fertile catchment soil, followed by MS6, US5, LS1, SR2 and US2, which are all fertile. The transition areas T1-T5, US3, MS2, MS3 and MS4 are relatively poor to slightly fertile in most soil fertility parameters.

3.4.3. Plot level

Soil productivity encompasses soil fertility plus all the other factors affecting plant growth, including soil management (Foth and Ellis, 1988). There is a strong positive correlation in productive soils between fertility and physical properties, so that highly productive soils have desirable physical properties and high fertility. In this section, graphical approaches are used to explore the relationships between soil productivity and individual soil fertility parameters, based on the data sets produced in this research. Then, numerical approaches are used to assign a weight for each individual soil fertility parameter and a fertility index is calculated for each plot.

3.4.3.1. Graphical approach

Soil sample Set 4 was used in this section because of its large population. This set of soil samples was collected in December 1999, so it was expected to have a close relationship with the crop yield produced in the following season, which was the maize 2000. Therefore, the relative maize yield (percentage of maximum) from 2000 harvest was plotted against the soil analysis data from soil sample Set 4. Instead of attempting to fit a continuous mathematical function through the scattered points, this simple graphic method divided the points into quadrants by a horizontal and a vertical line, which is fixed by eye. The maximum number of points falls in the lower left and upper right quadrants, and the minimum number of points is in the upper left and lower right quadrants. The point at which the vertical line intersects the *x*-axis is considered to be at the critical level for the relevant soil fertility parameters. The point at which the horizontal line intersects the *y*-axis separates soils with high response from those with low response.

Plant growth and yields are functions of many variables beyond the single nutrient under consideration. It is difficult to establish strong correlations in field studies, especially where the variables are not controlled. In Wang Jia Catchment, only available P had a good correlation with maize yield using graphic methods (Figure 3.4.2).

Soil pH

The highest yields were obtained in plots F10-2, 26 and 32. These plots have pH values of 6.7-6.8. There was not a clear association between relative yield and soil pH. The critical pH level under such circumstances was ~6.5. This means those plots with pH value in the lower left quadrant are likely to show large yield responses to increasing pH. The distributions of pH values in plots classified by the Chinese standard and using this tentative critical value of 6.5 are shown in Figures 3.4.3 and 3.4.4, respectively.

Total organic matter

The highest yield was obtained with total organic matter content of 2.2-2.3%. The critical total organic matter level under such circumstances was ~2.0%. Plots with total organic matter <2.0%, especially those falling in the lower left quadrant have a high probability of a large response to increased total organic matter content. There was a relatively large proportion of the plot population in the upper left quadrant, where

Figure 3.4.2. Plots of relative maize yield and soil fertility parameters.

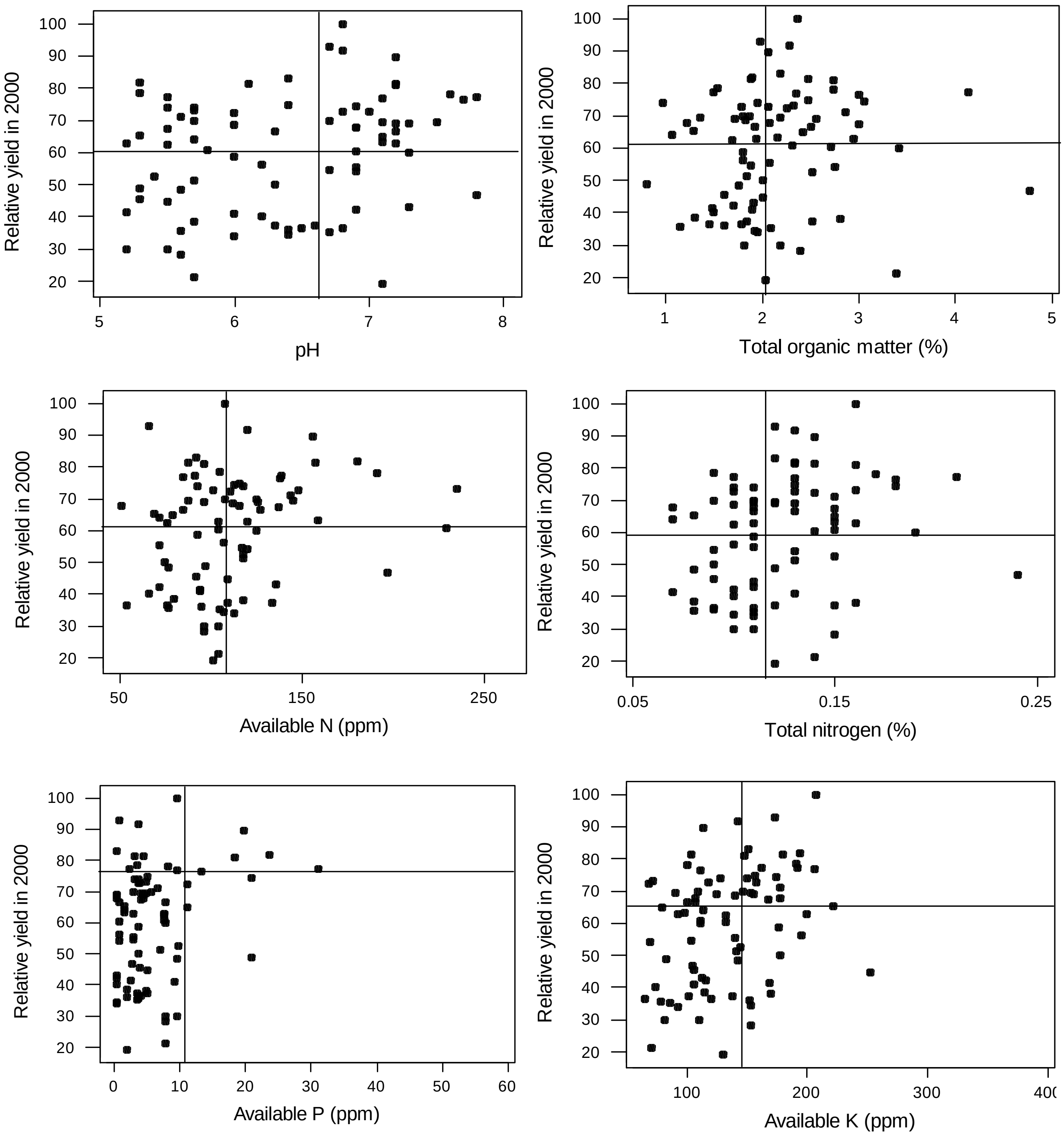


Figure 3.4.3. Distribution of 1999 soil fertility levels by the Chinese standard.

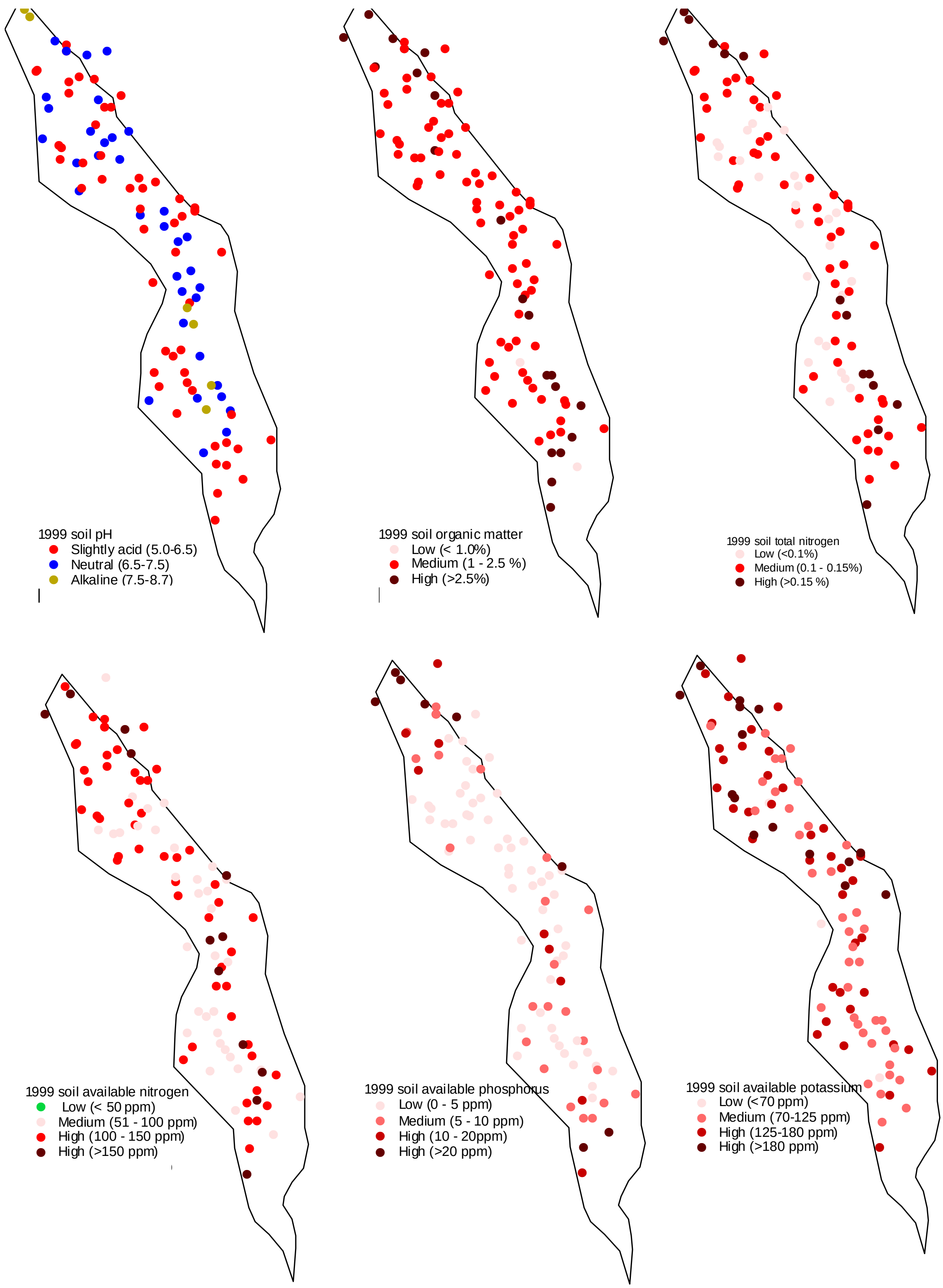
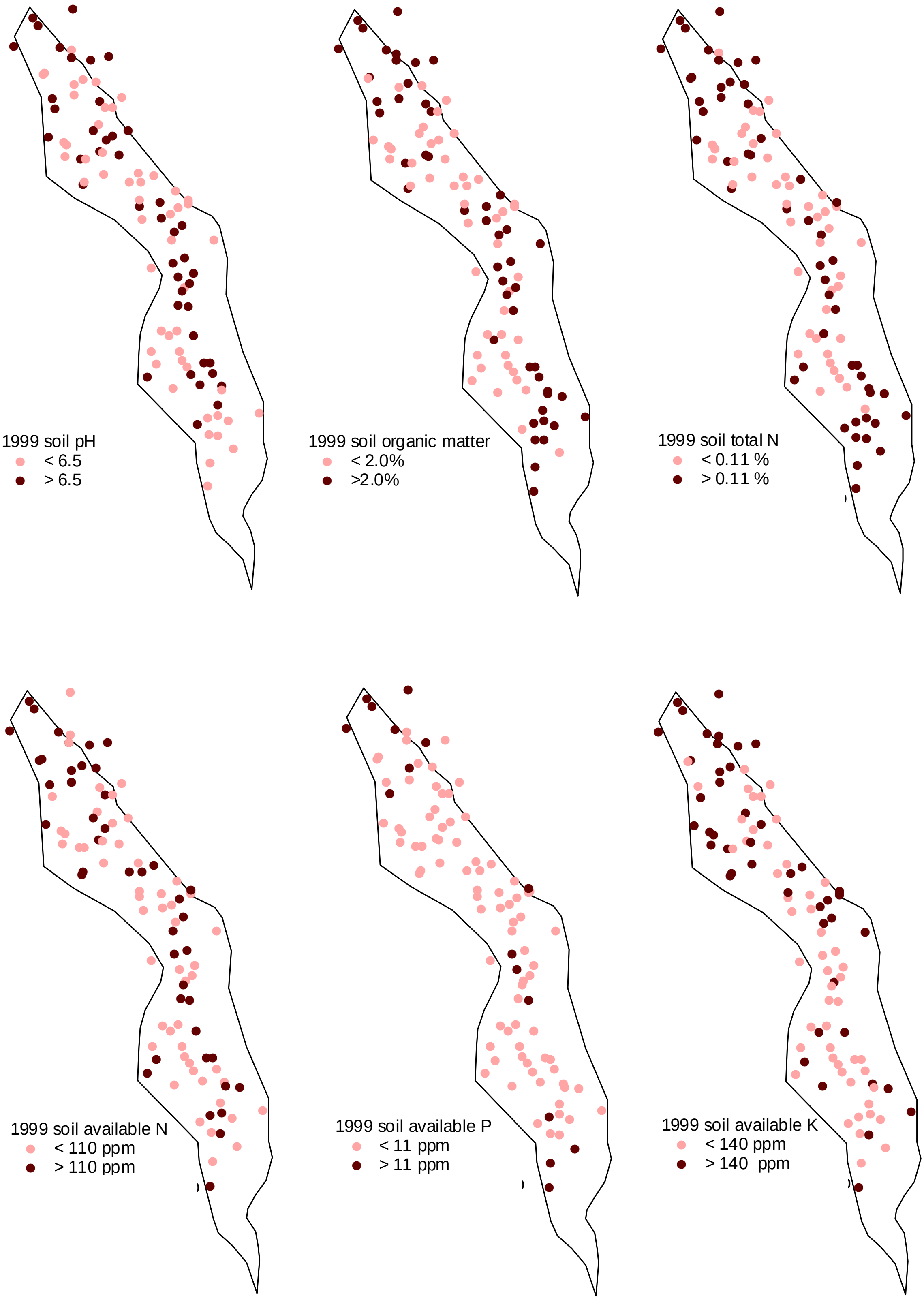


Figure 3.4.4. Distribution of 1999 soil fertility levels by the tentative critical values developed in this study.



relatively high yields were produced in the plots with relatively low organic matter contents. These may have been due to use of manure, inorganic fertilizer application or other soil properties. Only a few plots were in the lower right quadrant, where low yield was produced in plots with high organic matter contents, indicating other limiting factors. The distributions of plots with total organic matter classified by the Chinese standard and using this tentative critical value of 2.0% are shown in Figures 3.4.3 and 3.4.4, respectively.

Total nitrogen

The highest yield was obtained with total nitrogen contents of 0.12-0.15%. The critical total nitrogen level under such circumstances was ~0.11%. Since there is a significant positive correlation between soil organic matter and total nitrogen content, they have the similar graphical pattern. A relatively large population was in the upper left quadrant, where relatively high yields were produced in the plots with relatively low total N contents. This may have been due to N fertilizer applications prior to the 2000 season. Few plots are in the lower right quadrant, where low yield was produced in plots with high total N, indicating other limiting factors. The distributions of plots with total nitrogen classified by Chinese standard and using this tentative critical value of 0.11% are shown in Figures 3.4.3 and 3.4.4, respectively.

Available nitrogen

The graph for available N was similar to those for organic matter and total nitrogen. High yield was not necessarily related to high available N content, because urea applications were very common for maize production in the catchment. A few plots produced low yields with high available N contents. This may have been related to other management practices or limiting factors. The critical available N level under this specific soil-crop situation for the analysis method employed was ~110 ppm. This value is close to the current limit between medium and high levels of available N, which is 100 ppm. Some researchers have proposed ~100 ppm as the limit between low and medium levels of available N. The distributions of plots with available nitrogen classified by the Chinese standard and using this tentative critical value of 110 ppm are shown in Figures 3.4.3 and 3.4.4, respectively.

Available phosphorus

Available P had the strongest correlation with maize yield among the tested parameters. This meant that available P was a more important limiting factor than the other nutrients. Increasing P in most of the plots is likely to obtain a large yield response. This confirmed the field observed P-deficiency symptoms of purplish red leaves. The critical value of available P in Wang Jia Catchment for maize production was ~11 ppm. Most plots were in the lower left with only a few in the lower right quadrant. The distributions of plots with available P classified by the Chinese standard and using this tentative critical value of 11 ppm are shown in Figures 3.4.3 and 3.4.4, respectively.

Available potassium

Although K application is not a common practice in Wang Jia Catchment, the correlation between maize yield with available K is not as good as with available P possibly due to the influence of parent material and manure application. However, maize yield correlated better with available K than with available N, total N, organic matter and pH. The critical value was ~140 ppm. A considerable number of plots were in the upper left quadrant. The distributions of plots with available K classified by Chinese standard and using this tentative critical value of 140 ppm are shown in Figures 3.4.3 and 3.4.4, respectively.

3.4.3.2. The numerical approach

Regression analysis

In order to investigate the relationship between maize yield and soil analytical data, a linear regression analysis was carried out. Maize yield was regressed with the relevant soil analysis data (Table 3.4.7). Since many other variables are involved in maize growth and yield and they are different each year, only soil data Sets 2 and 4 can reasonably explain maize yield differences. These two sets were samples collected in 1999. Set 2 was collected in spring just before the 1999 maize growing season. Set 4 was sampled in winter before the 2000 maize season and had a relatively large population. Soil data Set 2 has more parameters and then can explain more variance in maize yield.

Principal component analysis

Information about the correlation among all variables used in the regression between yields and soil parameters is a suitable starting point to relate the contribution of soil fertility parameters to yield. Here only soil data Set 4 was further analysed. Pearson correlation coefficients are presented in Table 3.4.8. Correlation analysis showed that soil pH, total N, available N, available P and available K were significantly correlated

Table 3.4.7. Regression analysis between maize yield and relevant soil fertility parameters.

Maize yield	Soil data	N	Equation	R^2 (%)	P
1999	Set 2	20	yield (kg/ha)= 1003 + 833 pH + 3426 organic C(%) + 9425 organic N(%)+ 50.4 Ca^{++}(meq/100g) - 141 Mg^{++}(meq/100g) - 11626 K^{+} (meq/100g) + 146 P disp.(mg/ 100g) - 12.5 Mn (mg/ 100g) - 784 Zn (mg/ 100g)	74.4	<0.05
2000	Set 4	79	yield (kg/ha)= - 2188 + 654 pH - 1009 organic matter (%) + 15283 total N (%)+ 9.73 available N (ppm) + 30.9 available P (ppm)+ 15.5 available K (ppm)	32.8	<0.001
2002	Set 5	28	yield (kg/ha) = 4290 + 243 pH - 90 organic matter (%) - 11890 total N (%)+ 20.5 available N (ppm) - 7.8 available P (ppm)+ 2.44 available K (ppm) + 17952 total P(%) - 327 total K (%)	20.5	0.757 (NS)
2002	Set 7	28	yield (kg/ha) = 6236 - 35 pH - 585 organic matter (%) + 10102 total N (%)+ 3.6 available N (ppm) - 2.6 available P (ppm) - 1.32 available K (ppm)	3.2	0.993 (NS)

NS = Not Significant.

Table 3.4.8. Pearson correlation coefficients with P-value among maize yield and soil fertility parameters.

	Yield	pH	Total organic matter	Total N	Available N	Available P
pH	0.253 0.024*					
Total organic matter	0.113 0.317	0.379 0.001***				
Total N	0.243 0.030*	0.473 0.001***	0.862 <0.001***			
Available N	0.238 0.033*	0.143 0.161	0.555 <0.001***	0.654 <0.001***		
Available P	0.241 0.031*	0.153 0.134	0.506 <0.001***	0.623 <0.001***	0.480 <0.001***	
Available K	0.322 0.004**	-0.083 0.418	0.219 0.030*	0.192 0.059	0.199 0.049*	0.396 <0.001***

* Significant at P<0.05

** Significant at P<0.01

*** Significant at P<0.001.

with yield. Although organic matter was not significantly correlated with yield, it was significantly correlated with pH, total N, available N, available P and available K. In this case, principal component analysis was carried out to search for the main component. The result with eigenanalysis of the correlation matrix is presented in Table 3.4.9. Because of the large population, the first three principal components (PCs), which have the cumulative contribution of 84.1% are sufficient for extracting necessary information. These three principal components were then used during the following factor analysis to assign the weight value for each variable (soil parameter).

Table 3.4.9. Principal component analysis of soil data from sample Set 4.

Eigenvalue	3.1332	1.1928	0.7189	0.4586	0.3974	0.0991
Proportion	0.522	0.199	0.12	0.076	0.066	0.017
Cumulative	0.522	0.721	0.841	0.917	0.983	1
Variable	PC1	PC2	PC3	PC4	PC5	PC6
pH	0.257	-0.626	-0.599	-0.074	-0.397	0.14
Total organic matter	0.494	-0.125	0.053	-0.182	0.656	0.523
Total N	0.532	-0.158	0.066	0.013	0.208	-0.803
Available N	0.426	0.088	0.556	-0.38	-0.578	0.155
Available P	0.428	0.298	-0.063	0.81	-0.183	0.186
Available K	0.206	0.686	-0.566	-0.4	-0.041	-0.062

Principal component factor analysis and weight value

The communality for each parameter represented the contribution of this parameter to the total soil fertility variance (Table 3.4.10). The estimated weight value for each parameter was calculated based on its communality and sum of the total weight value is 1.0. For this soil data set, the synthetic parameter pH has the highest weight value, followed by available K and total nitrogen. Total organic matter, available N and available P have relatively low weight values. However, these weight values are not directly linked to crop yield. They only explain the contribution of each parameter to the variation of the soil fertility.

Soil Fertility Index

In quantifying the current state of soil fertility and as a base from which to monitor change with time, an index of soil fertility was calculated using the concepts of Sun *et* *al.* (1995) for the Soil Fertility Index and Karlen and Stott (1994) for the Soil Quality Index. For each soil parameter, a scoring function (fuzzy approach) and threshold were established based on the literature and Section 3.4.3.1 and thus are not very soil specific nor specific for land use (Table 3.4.11). Firstly, the scores for each soil parameter were multiplied by relevant weight values. Then the weighted soil parameters were summed up for each plot to give a soil fertility index (Figure 3.4.5).

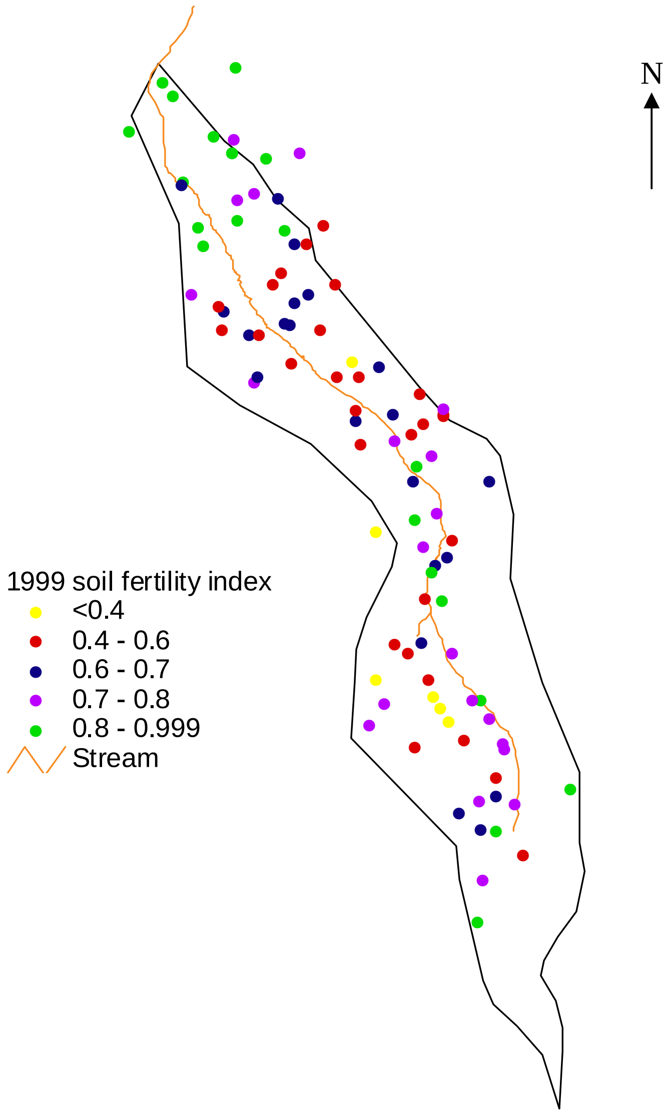
Table 3.4.10. Unrotated factor loadings, communalities and weight values.

Variable	Factor 1	Factor 2	Factor 3	Communality	Weight value
pH	0.455	-0.684	-0.508	0.933	0.185
Total organic matter	0.875	-0.137	0.045	0.787	0.156
Total N	0.941	-0.172	0.056	0.919	0.182
Available N	0.753	0.097	0.471	0.799	0.158
Available P	0.757	0.325	-0.053	0.682	0.135
Available K	0.365	0.749	-0.48	0.925	0.183

Table 3.4.11. Soil parameters, thresholds and scoring functions.

Soil parameter	Unit	Values of turning points	Scoring function
pH		$x_1 = 4.5$ $x_2 = 6.5$ $x_3 = 8.0$ $x_4 = 8.5$	$f(x) = 0.9\ (x-x_3) / (x_4-x_3) + 0.1$, where $x_3<x\leq x_4$ $f(x) = 1.0$, where $x_2<x\leq x_3$ $f(x) = 0.9\ (x-x_1) / (x_2-x_1)+0.1$, where $x_1\leq x< x_2$ $f(x) = 0.1$, where $x<x_1$ or $x>x_4$
Organic matter	%	$x_1 = 1.0$ $x_2 = 2.5$	$f(x) = 1.0$, where $x>x_2$ $f(x) = 0.9\ (x-x_1) / (x_2-x_1)+0.1$, where $x_1\leq x< x_2$ $f(x) = 0.1$, where $x<x_1$
Total nitrogen	%	$x_1 = 0.10$ $x_2 = 0.15$	$f(x) = 1.0$, where $x>x_2$ $f(x) = 0.9\ (x-x_1) / (x_2-x_1)+0.1$, where $x_1\leq x< x_2$ $f(x) = 0.1$, where $x<x_1$
Available N	ppm	$x_1 = 50$ $x_2 = 110$	$f(x) = 1.0$, where $x>x_2$ $f(x) = 0.9\ (x-x_1) / (x_2-x_1)+0.1$, where $x_1\leq x< x_2$ $f(x) = 0.1$, where $x<x_1$
Available P	ppm	$x_1 = 5$ $x_2 = 11$	$f(x) = 1.0$, where $x>x_2$ $f(x) = 0.9\ (x-x_1) / (x_2-x_1)+0.1$, where $x_1\leq x< x_2$ $f(x) = 0.1$, where $x<x_1$
Available K	ppm	$x_1 = 75$ $x_2 = 140$	$f(x) = 1.0$, where $x>x_2$ $f(x) = 0.9\ (x-x_1) / (x_2-x_1)+0.1$, where $x_1\leq x< x_2$ $f(x) = 0.1$, where $x<x_1$

Figure 3.4.5. Distribution of the Soil Fertility Index values within Wang Jia Catchment.



Since the soil nutrient content in the catchment is relatively low, it is rare to find a plot with toxic elemental concentrations. Normally the higher the soil parameters, the higher the Soil Fertility Index (Figure 3.4.5). The most fertile soils in the catchment are located in the narrow plain along the stream or in the alluvial plain close to the village. Most of the lowest Soil Fertility Index values are assigned to the soils in the upper west interfluve. Generally, the Soil Fertility Index is quite variable in the catchment. Regression of maize yield in 2000 with Soil Fertility Index gave a R^2 16.88%($F = 15.64$, $P < 0.001$, $n = 79$). The regression equation is:

Crop yield (kg/ha) = 2519 + 3870 Soil Fertility Index 3(2)

3.5 Comparison of different sampling strategies

3.5.1 Introduction

Developing the concepts of and formulating the scientific basis for soil testing has been one of the most important contributions by soil scientists to agricultural production. Soil tests for fertility evaluation are traditionally performed on one composite sample that represents an entire field. Therefore soil testing which provides useful and reliable results depends on the soil sampling strategy employed. A routine soil sample weighs approximately one kilogram based on Chinese methods. This represents one part out of each one million parts of the average top 15cm of 100 m^2 of soil. Soil sampling is the largest source of error in soil fertility evaluation programmes. Obtaining a representative soil sample is the key to a successful soil testing.

Soil is a heterogeneous material. Soil sampling error is closely related to soil variability in a sampling unit. Cultural practices and crop production influence soil chemical and physical properties and thus modify inherent soil variability. Variability in soil fertility often reflects past soil management, as well as differences in inherent soil characteristics. Changes in farm management practices have been dramatic and have important consequences for soil testing. Reduced tillage and modern cultivation techniques require re-evaluation of soil sampling procedures. Analysis of small-scale variability has practical uses in managing soil fertility for a given field. It may be necessary to have specialized soil sampling procedures for different farm management practices.

Reduced and no-till systems result in stratified physical and chemical characteristics of the surface soil. As suggested in Montana, USA, when soil sampling, the plough layer should be divided into two depths, 0-5 and 5-15 cm. Cores are sampled between the rows if starter fertilizer was banded in past years. If all fertilizer is applied in a band for irrigated crops, sample three to four cores that are spaced equally between the ridge or row. This evens out chances of sampling directly in a fertilizer band (Jacobsen, 1999). Soils that have been deep banded dictate taking an increased number of cores. Several sets of cores should be taken from 10 to 15 locations at a distance equal to one-half the fertilizer band width near the row placed band. Also the fertilizer bands in fields where row crops have been grown should be avoided, because samples taken from these locations would not be typical of the soil in the rest of the field and so including them could produce misleading results (Baird, 2000).

In Wang Jia Catchment, soil was ploughed by labour using hand spade or hoe. Manure and fertilizer were applied in bands or pits. Maize, wheat and tobacco were planted in rows with maize seed sown in fertilized pits. These farm management practices are common in this region and were expected to cause large fertility variations in a single plot. During previous research work in the catchment, the composite samples were collected before and after maize production using a traditional random sampling procedure. This sometimes caused problems for the interpretation of the results, due to the large intra-plot variation (Huang, 2001; Wang, 2003). Therefore, it is necessary to quantify the intra-plot variation to provide useful information for forming an appropriate sampling procedure adapted for soil fertility evaluation under such circumstances.

3.5.2. Intra-plot variation of soil fertility

Data presented here were from soil sample Set 6. These samples were collected from a field experimental plot which has had down slope cultivation since 1999 (Wang, 2003). The plot was planted with maize in summer and wheat in winter 1999, 2000 and 2001. For maize planting, the soil was ploughed by hand hoeing several days before planting. On the sowing day, pits were dug along the downslope direction. Then seeds were sown and manure, urea and single superphosphate were applied in or surrounding the pits. The pits were then covered with soil and finally watered. The application rates as base fertilizers for manure, urea and superphosphate were 15,000, 300 and 225 kg/ha, respectively. Two top dressings totalling 450 kg/ha urea were applied during the maize growth season. For wheat planting, furrows were employed instead of pits. The application rates as base fertilizers for manure, urea and superphosphate were 7,500, 225 and 600 kg/ha, respectively. One top dressing of 75 kg/ha urea was applied two months after sowing in 2000. Soil sample Set 6 was collected after the maize season on the harvest day of 07/10/2001. Each 10 samples were collected from the location of pits and inter-row and one composite sample was taken from the whole plot, using traditional random sampling strategy with “W” pattern.

Six soil fertility parameters were analysed in Yunan Agricultural University. The comparison between pits and inter-rows shows large intra-plot variation (Table 3.5.1). There were significant differences in terms of soil pH, total organic matter, total N, available N, available P and available K. Due to the residual effect of manure and fertilizer applications, soil total organic matter, total N, available N, available P and available K in pits were significantly higher than that in inter-rows. Because the manure had a pH of ~7 (Wang, 2003), the pH in pits was higher than inter-rows.

Table 3.5.1 Paired T-Test results of soil fertility parameters between pits and inter-rows

Analysis	Unit	Variable	N	Mean	StDev	T-Value	P-Value
pH		Pit	10	5.68	0.32		
		Inter-row	10	5.17	0.44		
		Difference	10	0.52	0.34	4.80	<0.001
Total organic matter	%	Pit	10	1.84	0.18		
		Inter-row	10	1.15	0.13		
		Difference	10	0.69	0.20	10.60	<0.001
Total nitrogen	%	Pit	10	0.17	0.06		
		Inter-row	10	0.11	0.03		
		Difference	10	0.06	0.06	2.83	<0.05
Available nitrogen	ppm	Pit	9	113.78	12.09		
		Inter-row	9	85.22	24.98		
		Difference	9	28.60	30.3	2.83	<0.05
Available phosphorus	ppm	Pit	10	26.89	9.71		
		Inter-row	10	13.81	4.29		
		Difference	10	13.08	11.50	3.59	<0.01
Available potassium	ppm	Pit	10	140.70	24.01		
		Inter-row	10	73.10	8.03		
		Difference	10	67.60	22.87	9.35	<0.001

For most of the tested soil fertility parameters, pits had higher standard deviations than inter-rows except for soil pH and available N. The high standard deviation of available N may be related to the high mobility of nitrate, although the N was applied as urea. Normally, urea is transformed into nitrate in upland soil within one to three weeks, depending on soil temperature and moisture conditions. Nitrates then move with water movement from upslope to downslope and from topsoil to subsoil. The large variation from pits may bring large errors to composite soil samples if the composite sample includes cores from pits. In order to eliminate the sampling error from a composite sample, it may be wise to avoid the locations where manure or fertilizers have been applied.

One-sample T tests were conducted, taking the relevant soil parameter data from the composite sample as the tested means (Table 3.5.2). In terms of most soil fertility parameters, pit values were significantly different from composite, except for pH. Inter-rows were only significantly different from the composite in terms of pH, available N and available K. Combining with Table 3.5.1, the results suggest if composite samples were taken only from inter-rows, the results would have been similar to traditional random sampling and the risk of sampling error would have been reduced.

Table 3.5.2. One-Sample T results for the composite sample.

Analysis	Unit	Variable	Mean	StDev	T	P
pH		Pit Inter-row Composite	5.68 5.17 5.70	0.32 0.44	-0.18 -3.82	0.864 <0.01
Total organic matter	%	Pit Inter-row Composite	1.84 1.15 1.24	0.18 0.13	10.30 -2.08	<0.001 0.067
Total nitrogen	%	Pit Inter-row Composite	0.17 0.11 0.12	0.06 0.03	2.86 -0.73	<0.05 0.484
Available nitrogen	ppm	Pit Inter-row Composite	113.30 85.22 62.00	11.50 24.98	14.11 2.79	<0.001 <0.05
Available phosphorus	ppm	Pit Inter-row Composite	26.89 13.81 12.54	9.71 4.29	4.67 0.94	<0.001 0.374
Available potassium	ppm	Pit Inter-row Composite	140.70 73.10 80.00	24.01 8.03	7.99 -2.72	<0.001 <0.05

Results summary

The results can be summarized as follows:

1. Hypsometric curves of Wang Jia Catchment and Wang Jia area have similar patterns. The curves are reasonably parallel between $0<h/H<0.42$ and $0.61<h/H<1$. The median altitude of Wang Jia Catchment is slightly higher (2,100 m) than Wang Jia area (2,060 m). This is mainly due to the influence of a pediment remnant in Wang Jia Catchment between 2,100 m ($h/H = 0.46$) and 2180 m ($h/H = 0.61$). The comparison of natural slopes between Wang Jia Catchment and the Wang Jia area showed a slightly higher percentage area of 10-15° slopes in Wang Jia Catchment. In this area, most slopes are <25° and less than 8% of the area has a slope >25°.

2. The interpretation of a satellite image concluded that land cover in Wang Jia area and Wang Jia Catchment was similar during winter. Wang Jia Catchment has a high percent area with negative NDVI values, indicating less green biomass compared to the Wang Jia area due to the influence of small alluvial plains in Wang Jia area.
3. In Wang Jia Catchment, annual rainfall in 1999, 2000, 2001 and 2002 was 1028.7, 793.4, 857.8 and 759.6 mm, respectively. The rainfall data for 2001 and 2002 were incomplete, especially in 2002. The amount of rainfall was relatively high in 1999 and low in 2000. There was an unexpected heavy hail storm (09 August 2001). Allowing for the incomplete record in the rainy season, August 2002 had the highest monthly rainfall among the four years. Most annual rain fell in summer from May to September, sometimes to October. The combined effects of rainfall, humidity and wind made the winter and early spring very dry. The lowest air relative humidity occurred in March or April, varying in different years.
4. The annual mean air temperature was ~15 °C in Wang Jia Catchment. December or January had the lowest monthly mean air temperature, which was ~7.4-9.0 °C. The warmest months were June, July or August, with monthly mean air temperatures of between 21.1-22.6°C. There could be a large intra-catchment temperature variation due to the major differences in elevation. The temperature difference could be as great as 5.2˚C in winter and 3.1˚C in summer.
5. Three main lithologies have been identified: shale, sandstone and dolomite (or dolomitic limestone). The catchment summit was dominated by sandstone, which consisted of 6% of the catchment surface. Shale was observed in the catchment foot and upper part of catchment (39%). Dolomite was distributed in the middle part of the catchment and occupied 55% of the catchment area. In certain parts of the catchment, lithology was complex.
6. Generally, soil bulk mineralogy was dominated by quartz (65.8%), with subsidiary amounts of K-feldspar (9.0%), illite and small amounts of plagioclase feldspar and chlorite. The two major clay minerals found were illite (53.4%) and chlorite (39.6%), with minor kaolinite (0.4-24.9%). The results suggested that the soils were still strongly influenced by their geological parent material.
7. In general, the catchment was described as Summital Relief (SR) which occupied 2,470-2,200 m in elevation, the Upper Sector (US) from 2,200-2,070 m, the Middle Sector (MS) from 2,070-1,940 m and the Lower Sector (LS) from 1,940-1,860 m. The topography of the catchment was rather complicated and could be classified into 13 slope units.

8. Most areas in Wang Jia Catchment were cultivated as sloping terrace (45.8%) and terrace (8.5%). There were some woodlands of pine or mixed trees, abandoned terraces, bushes, bare soils and grass.
9. At the summital relief and alluvial plain where soil was influenced by sandstone, soil texture tended to be more sandy or silty (normally silt loam). On the interfluves where soil was influenced by shale or dolomite, soil texture tended to be more clay-rich (silt loam to clay loam). Soil under shale or sandstone influence tended to be acidic, while the dolomite tended to increase soil pH. Shale tended to produce yellowish, sandstone reddish brown and residual product of dolomite reddish soil colours. However, these three lithologies are frequently mixed as alluvial in the alluvial plain or colluvial materials on the interfluve, which makes the soil pattern very complex. Soil properties are very dependent on location. The influence of human activities makes the interpretation of soil properties more difficult. Based on field survey and laboratory analysis, 16 geomorphopedological units and 5 transition units were identified.
10. There was a considerable potential to increase maize yield with modified and innovative cropping practices, although the maize yield was relatively high in the catchment, compared to the Yunnan average. The yearly mean yield of maize was in the order of 2002 > 1999 > 2000> 2001. The mean yield for locations was in the order of lower part > middle part > upper part. Geounits MS6, LS1 and MS3 tended to have high yields, while T1, T3 and US3 had low yields.
11. Increasing number of farmers used maize cultivar DF4 in the middle and lower catchment and HD4 in the upper catchment. As a soil conservation practice, contour cultivation did not show much advantage for maize yield, except in 2002. Polythene mulch tended to increase maize yield, except for 2001 when hail damage decreased final yield considerably. Few farmers used irrigation systems in the catchment. Manure and urea applications were relatively common and were significantly positively correlated with maize yield.
12. Considerable variation existed in soil fertility parameters (pH, organic matter, total N and available N, P and K) in the catchment. Soils were slightly acidic to neutral/calcic or calcareous. Except for available N, the other soil parameters ranged from low to high levels. Some half of the plots had low to medium levels of organic matter content, medium levels of total N content, high levels of available N, low levels of available P and high levels of available K, compared with China’s national standards, according to the analytical method employed.

13. In general, geounits in the flat or concave position (alluvial plain and catchment outlet) had relatively good soil fertility compared to the convex or steep slopes (the interfluves), probably due to erosion, human activities and parent materials. Meanwhile, geounits close to the village tended to have good fertility compared to geounits far from the village. LS2 was the most fertile soil in the catchment, followed by MS6, US5, LS1, SR2 and US2, which mostly have high soil fertility parameter values. The transition areas T1-T5, US3, MS2, MS3 and MS4 were relatively poor to slightly fertile in most soil fertility parameters.
14. Soil fertility evaluation using graphical approach showed that for maize production in Wang Jia Catchment, the critical values of pH, soil organic matter, total N and available N, P and K were 6.5, 2.0%, 0.11%, 110 ppm, 11 ppm and 140 ppm, respectively.
15. Soils located in the narrow plain along the stream or in the alluvial plain close to the village had relatively high Soil Fertility Index values. Soils in the upper west interfluve had relatively low Soil Fertility Index values. Regression of maize yield with Soil Fertility Index gave R^2 16.88% ($F = 15.64$, $P < 0.001$, $n = 79$). The regression equation is :

    Crop yield (kg/ha) = 2519 + 3870 Soil Fertility Index.
16. Due to the residual effect of manure and fertilizer applications, soil total organic matter, total nitrogen, available nitrogen, available phosphorus and available potassium in pits were significantly higher than in inter-rows. The pH in pits was more neutral than inter-rows. For most of the tested soil fertility parameters, pits had higher standard deviations than inter-rows, except for soil pH and available nitrogen. In terms of most soil fertility parameters, pit samples yielded results which were significantly different from the composite sample, except for pH. These results suggest if composite samples were taken only from inter-rows instead of being randomly compiled across the plot, the results would have been similar and the risk of sampling error would have been reduced.

Chapter 4. Discussion and Conclusions

Introduction.

In this Chapter, the findings of four years of results are discussed. Firstly, the reference value of the soil information for similar catchments in the region was discussed. Secondly, soil pedogenesis is discussed. Thirdly, crop fertilization based on soil fertility evaluation, intra-plot soil fertility variations and a soil fertility index as an indicator for monitoring effect of land management are discussed. Fourthly, the influence of rainfall and temperature on crop management performance, selection of maize cultivar, contour cultivation and polythene mulch are discussed and recommendations made. Then, a generic protocol for an integrated land information system in humid subtropical highlands is proposed. Finally, there is a discussion of the limitations of the study and general conclusions, with suggestions for future work.

4.1. Reference value of soil information system

Soil information systems (SIS) and land information systems (LIS) are in demand for use in many areas, such as agriculture, urban planning and industrial and municipal waste disposal (Chandrasekhar, 1995; Bartsch *et al.,* 1997; Zhang *et al.*, 2001; Huang *et al.,* 2002). Most studies of land information or soil information systems normally focus on the system structure and the computing program (Xiang, 2001; Zhou, *et al.*, 2000; Wei, 2002). The involvement of soil scientists and relevant experts in applied sciences are lacking. Although digital soil map information exists in certain countries or regions (Zhang *et al.,* 2001), their application in real agricultural production is rare due to inappropriate scale and the poverty of relevant information (Bouma and Bregt, 1988). A national digital soil map is not available in China, nor is there a provincial soil map of Yunnan. Therefore, accumulation of a soil information system with GIS will make an important contribution to the forthcoming third national soil survey in China, especially in Yunnan Province.

4.1.1. Construction of a soil information system

Based on the air-photography and a topographical map, supplemented by considerable data sets from a series of field surveys and laboratory analyses, a digital soil information system has been initiated using Arcview software. This system includes information on climate, topography, geology, biology and soil characteristics. As an open-ended system, more information can be added in the future when it is available, such as socio-economic information. Most information has been stored at plot level or combined into a smaller number of geounits. This information can be easily accessed, extracted and processed when required for future applications. In this study, the soil characteristics information was used in soil fertility evaluation, while the information from farmers' survey cards was used to describe the agrosystem within Wang Jia Catchment. The soil information system built up in such a structure is not only suitable for providing the baseline information before land use changes, evaluating agricultural practices and monitoring effects of land use changes afterward in the Catchment, but also for designing, evaluating and monitoring sustainable land management practices in the region.

4.1.2. Reference value of this soil information system in this region

The reference value of the soil information system in this region was based on the representativeness of Wang Jia Catchment within this region. The comparison of Wang Jia Catchment with similar catchments in the region in terms of geomorphological criteria and land cover criteria showed good similarity. As a typical catchment in this region, Wang Jia Catchment had a similar hypsometric curve to one for the region. Most land in Wang Jia Catchment and this region have slope degrees between 0-15˚. Less than 8% area has a slope >25˚, where any cultivated land should be returned to forest or grassland according to the Chinese Government. The interpretation of satellite images also showed the similarity of land cover during winter when the catchment was very dry and biomass very low. Satellite images taken during summer when maize was growing would be more useful for the interpretation of land use or cover. However, it is difficult to obtain a clear image during the summer, due to the extensive cloud cover during monsoon rains.

When using the information from the soil information system as a reference for similar catchments in this region, the complicated combinations of biophysical factors should be born in mind. The geology and geomorphology are quite complicated and play a significant role in soil properties and agricultural production. The simple information can be easily deduced from every single aspect of geology, morphology and biology. However, the synthesis of the combined effect of all these aspects should be referenced carefully and interpreted site-specifically.

4.2. Pedogenesis information

In 1883, the Russian soil scientist Vasilli Dokuchaev identified five soil-forming factors: parent material, climate, topography, biota and time. Although the model has been subject to modification, Dokuchaev's concepts remain at the core of pedology (Fullen *et al.,* 1999b). Soils are often defined in terms of these factors as "dynamic natural bodies having properties derived from the combined effects of climate and biotic activities, as modified by topography, acting on parent materials over periods of time" (Brady and Weil, 1999).

4.2.1 Parent material

Three main lithologies have been identified in Wang Jia Catchment: shale, sandstone and dolomite. The catchment summit was dominated by sandstone. Shale was observed at the catchment foot and the middle upper part of the catchment, while dolomite was distributed in the middle part of the catchment. Normally the sandstone is a feldspathic orthoquartzite in decreasing order of frequency, quartz, K-feldspar, chalcedony and mica. The shale is laminated, yellowish or grey in colour. One of the shale's main mineralogical characteristics is high mica content. Dolomite has a massive aspect. Under the microscope the rock shows a (dolo)sparitic or a micro(dolo)sparitic fabric; rather large crystals forming the bulk of the rock or being scattered in a fine matrix of micritic calcite and/or dolomite. Detrital quartz and mica are generally present in minor amounts.

The nature of parent material profoundly influences soil characteristics. Due to the complicated topographic features of the catchment, the above mentioned three lithologies frequently work together as colluvial or alluvial parent materials, although some could be residual materials. At the summit and alluvial plain, where soil is influenced by sandstone, soil texture tends to be more sandy or silty, normally a silt loam. At the interfluves, where soil is influenced by shale or dolomite, soil texture tends to be more clay, silt loam to clay loam. Soil under shale or dolomite influence tends to be acidic, while the dolomite tends to increase soil pH. Shale tends to have yellowish, sandstone reddish brown and residual product of dolomite reddish soil colours.

4.2.2. Climate

Climate is perhaps the most influential of the four factors acting on parent material, because it determines the nature and intensity of weathering. The principal climatic variables influencing soil formation are effective precipitation and temperature, both of which affect the rates of chemical, physical and biological processes (Brady and Weil, 1999).

In Wang Jia Catchment, annual rainfall is ~1000 mm. Most falls in the summer season from May to September, sometimes to October. The winter and early spring are very dry. The amount of annual rainfall and seasonal distribution pattern may allow water to penetrate into the regolith, stimulating weathering reactions and helping differentiate soil horizons in the summer time. However, the steep slope, may reduce water penetration into the soil by producing runoff. The soil is not very developed, especially in convex positions (the interfluves).

The annual mean air temperature is ~15°C in Wang Jia Catchment. December or January have the lowest monthly mean air temperature, which was ~7.4-9.0°C. The warmest month was June, July or August, which had a mean monthly air temperature of 21.1-22.6°C. This temperature regime is rather like a warm temperate region due to the high elevation (Fullard, 1976), although Wang Jia Catchment is located in the subtropics. Zhao (1986) also classified Yunnan in the temperate to subtropical Yunnan-Guizhou Plateau. This may provide another explanation that the soil in Wang Jia Catchment is not the Ultisol as might have been expected in this region.

4.2.3. Topography

Topography can hasten or delay the work of climatic forces. Steep slopes generally encourage erosion of the surface layers and allow less rainfall to enter the soil before running off, thus preventing soil formation from advancing ahead of soil destruction. The concave or relatively level positions receive runoff from adjacent sloping sites and have a moister water regime. From up-stream to down-stream and from parent material to topsoil in Wang Jia Catchment, different generations of deposits were observed as colluvium in lower slopes and alluvium along the stream. Soil stoniness varies from stony (15-50%) on steep slopes to slightly stony (<15%) on concave or level positions and soil thickness from 40->120 cm. The soils of the alluvial plains are generally more fertile than in the interfluves. On the most sensitive convex positions, topsoil is acidic, low in total organic carbon and relatively base unsaturated. In the most favourable concave positions, topsoil is calcic/carbonated, higher in total organic carbon and base saturated. Slope aspect affects soil water and temperature and thus influences soil formation processes. Topography often interacts with vegetation to influence soil formation (Brady and Weil, 1999).

4.2.4. Biota

Natural vegetation influences soil properties in many aspects, such as organic matter accumulation, biochemical weathering and nutrient cycling. Litter falling from coniferous trees (e.g., pines and firs) will recycle only small quantities of calcium, magnesium and potassium compared to those recycled by litter from some deciduous trees. Thus, soil acidity is more strongly developed under most coniferous vegetation than under most deciduous trees. In the middle and upper Wang Jia Catchment, several pieces of pine woodlands existed, the main pines were *Pinus yunnanensis* Franch and *Pinus armandii* Franch. *Rhododendron speciferum* Franch was also observed in this area, which indicates acidic soil conditions. The main deciduous tree in mixed woodlands was *Alnus nepalensis* D.Don.

Natural vegetation is limited to the steep slopes and upper and summit parts of the catchment. Most of the catchment is cultivated and thus influenced by human activities, especially the relatively level or gently sloping sites. The main summer crops used to be maize and tobacco, but only maize during 1999-2002. Winter crops are mainly wheat and pea. The cultivated plots belong to many farmers with different management levels and it is impossible to track the complete history of agricultural management.

4.2.5. Time

Soil forming processes take time to show their effects. Where referring to a “young” soil, it is relates to the degree of weathering and profile development (Brady and Weil, 1999). In Wang Jia Catchment, two major clay minerals found are illite (53.4%) and chlorite (39.6%), with minor kaolinite (0.4-24.9%). The results suggest that the soils are still strongly influenced by the geological parent material from which they are derived. They are not the intensely weathered Ultisols as expected in this region. Ultisols have the dominant clay minerals of kaolinite and gibbsite or other oxidic clays (Foth and Ellis, 1988). The soils are young and soil profiles are not well developed and differentiated in term of pedogenesis in Wang Jia Catchment.

4.3. Soil fertility

Four years is a relatively short period over which to monitor general changes in soil fertility due to land management change or cultivation practice, especially when the plots received different manure and fertilizers every cropping season. Consequently, it was difficult to find and interpret consistent changes in soil fertility parameters without fixed management levels. Although significant changes were detected in some of the soil fertility parameters, these may have been short-term changes due to changes in cropping practice, especially manure and fertilizer application. Soil fertility is an important component of crop productivity and agricultural sustainability. Soil fertility was evaluated in this study as a basic component for crop production and will serve as a baseline for monitoring soil fertility changes in the future, which contribute to monitoring agricultural sustainability due to land management change. Johnston and Powlson (1994) reported that 20 years are needed for changes in soil organic matter to be measured reliably, whereas easily detected changes in readily soluble P and K in soil might be evident after 10 years in temperate climates.

4.3.1 Soil fertility evaluation using the category approach

Soil fertility is conceived as the capacity of a soil to provide plants with nutrients. Soil nutrient contents are influenced by soil inherent fertility and agricultural practices, especially manure and fertilizer application. Meanwhile, efficient fertilizer application programmes should be based on effective soil fertility evaluation. In terms of fertilizer recommendations in practice, soil fertility parameters were normally treated independently, although some systematic approaches exist such as diagnosis and recommendation integrated systems (Beaufils, 1973; Dev, 1997; Letzsch and Sumner, 1983; Sumner *et al.*, 1983). Many of the soil testing laboratories classify the fertility level of soils as very low, low, medium, high and very high (Cope and Rouse, 1973), based on the quantity of nutrient extracted by selected analytical methods (Eckert, 1987; Havlin *et al.*, 1999; Sanchez, 1976). Soil fertility is only one of the factors influencing plant growth, but in general there is a greater chance of obtaining a response from a given nutrient with low soil test results.

Soil pH is an indicator of soil acidity and reflects the chemical and mineralogical environment in that soil, and thus the pH is one of the most important factors affecting soil fertility and so is commonly managed to increase crop productivity. In Wang Jia Catchement, some 75% of the soil pH data were slightly acid to neutral. Soil pH ranged from 5.2-8.0, which is relatively favourable for maize growth (Sys, 1991). Geounit T4 and US3 on shale, SR2 on sandstone and T5, MS2 and MS3 on dolomite with influence of colluvium of shale or sandstone and shale had relative low pH values (<6.0). LS2, MS6, US4 and US5 along the narrow alluvial plain had direct influence of dolomite and strong influence of human cultivation and had relatively high pH (>7.0). In general, liming is not necessary in maize production. However, maize yield had a significant correlation with soil pH, regardless of the other interdependent parameters. ($r = 0.253$, $P < 0.05$, $n = 79$). This may mean that agricultural practices which somewhat increase soil pH may also increase maize yield.

Soil organic matter content is the most critical soil fertility parameter, because of its influence on many biological, chemical and physical characteristics inherent in a productive soil. It provides much of the cation exchange and water holding capacities of surface soil. Certain components of soil organic matter are largely responsible for the formation and stabilization of soil aggregates. Soil organic matter also contains large quantities of plant nutrients and acts as a slow-release nutrient storehouse, especially for nitrogen. Furthermore, organic matter supplies energy and body-building constituents for most of the micro-organisms. In addition, certain soil organic compounds have direct growth-stimulating effects on plants. For all these reasons, enhancing the quantity and quality of soil organic matter is a central factor in improving soil quality (Brady and Weil, 1999).

In Wang Jia Catchment, <25% of plots had a low level (<1.0%), >50% of plots had a middle level (1.0-2.5%) and only ~25% had a high level (>2.5%) of soil organic matter content according to China's standards. For the cultivated soil, LS2 at the catchment outlet had the highest organic matter content of 3.37%. Then followed US5 on the upper alluvial plain with total organic matter of 2.89%, followed by LS1, MS6, US2 and US4. Although soil organic matter did not have a significant correlation with maize yield, it is significantly correlated with total nitrogen ($r = 0.86$, $P < 0.001$, $n = 98$). Regression analysis showed that maize yield was significantly correlated with manure application in 2002. The determination of correlation R^2 was 14.9% ($P < 0.001$, $n = 97$). This may indicate that manure application is an effective practice in Wang Jia Catchment, especially on areas where soil organic matter is low.

Total nitrogen is a soil parameter that is closely related with soil organic matter and available N. More efforts have been, and are being, spent on the management of N than any other mineral element (Stevenson, 1982; Hauck, 1984). Globally, N deficiencies are widespread among plants (Brady and Weil, 1999). In many unfertilized soils, crop growth is limited by low supply of one or more of the major nutrients N, P and K, while there is a relatively ample supply of secondary and trace elements (Janssen *et al.,* 1990). N is generally the most limiting nutrient for crop production (Foth and Ellis, 1988).

In Wang Jia Catchment, 25% of total nitrogen content is at a high level (>0.15%), ~50% of the samples had total nitrogen at middle level (0.10-0.15%) and ~25% of them were at low level (<0.10%). Geounit LS2 has the highest total nitrogen content, followed by US5 and then SR2. LS2, US5 and SR2 also had the total nitrogen contents at high levels (>0.15%). The transition areas T4 and T2 had relatively low total nitrogen contents. Total nitrogen was significantly correlated with maize yield (r = 0.243, P <0.05, n = 80).

Available N is the soil parameter normally used for determining N fertilizer rate in the following crop, especially for fast growing short season crops. It was closely related to the crop N uptake and crop yield in many areas (Zhang *et al.,* 1999). In Wang Jia Catchment, >50% plots investigated had available nitrogen at a high level (>100 ppm), none of them was at a low level (<50 ppm). However, these available nitrogen indices are slightly out of date due to intensification of crop production and resulting depletion of soil fertility. Geounit LS2 had both the highest total nitrogen content and available nitrogen content, followed by SR2, MS3, US5, LS1, US2 and MS6. All these units have high levels of available nitrogen content (>100 ppm). Only geounits MS4, T2, T4 and US3 had medium levels of available nitrogen content (50-100 ppm). Regression analysis showed that maize yield was significantly correlated with urea application in 2002. The coefficient of determination R^2 was 10.7% (r = 0.327, P <0.01, n = 97). This may indicate that N fertilizer application is an effective practice in Wang Jia Catchment, especially in the areas where available nitrogen content is relatively low. Normally, the chance of N fertilizer response is better in the plots with lower soil available nitrogen content.

Available P is the parameter normally used for P fertilizer application recommendations. Management of P is second only to management of N in its importance for crop production. More P deficiencies were reported with the increased N fertilizer application and thus increased crop yields. Since the major proportion of total P is in unavailable forms, available P is measured for most fertilizer recommendation programmes. In China, red soil is characterized as low in total and available P (Zhang *et al.*, 1999). However, Yunnan Province is the largest P fertilizer producer in China and P application is very common for tobacco production in Yunnan. The long residual effect of P fertilizer must be taken into consideration when evaluating soil P status where tobacco used to be cropped.

In Wang Jia Catchment, <25% plots had available P at a high level (>10 ppm), <25% at a middle level (5-10 ppm) and >50% at a low level (<5 ppm). Geounit LS2 had the highest available P content, followed by SR2, LS1, MS6, US2, US5 and MS2. LS2 and SR2 had a very high level of available P content (>10 ppm). LS1, MS6, US2, US5, MS2 and US3 had medium levels, while MS3, MS4, MS5 T1, T2, T3, T4, T5 and US4 had low levels, especially the transition areas T1-T5. Regression analysis show that maize yield was significantly correlated with soil available P content ($r = 0.241$, $P<0.05$, $n = 80$) in 1999. This may indicate that increasing soil available P is an effective practice to increase maize yield, especially in areas where available P content is relatively low. However, the regression of maize yield with superphosphate application did not show significant correlation for the 2002 data, which may be due to manure and compound fertilizer applications, which also contribute soluble P to plant growth.

Available K is progressively becoming important in fertilizer recommendations with increased crop yield and decreased manure applications in China. Some 59.1% of arable land is deficient in soil N and P and 22.9% in soil K (Zhang *et al.*, 1999). Because of the intensification of crop production and resulting depletion of soil fertility, China has become much more dependent on mineral fertilizer use. The Chinese Government imports K fertilizer from Canada and Europe. These were mainly used in South China. Red soil was reported as the most K deficient soil, especially in Southeast China, where annual rainfall is high (Zhang, 1999). In Yunnan, N-P-K compounds and potassium sulphate were applied to soil wherever tobacco was cropped and this may make major differences in soil K status.

In Wang Jia Catchment, soil K was influenced mainly by parent material, K-containing fertilizers and manure applications. Over 50% of plots had available K at a high level

(>125 ppm), >25% at a middle level (70-125 ppm) and only 1% at a low level (<70 ppm). Geounit LS2 had the highest available K content, followed by T4, MS2, LS1, MS3, T5, T3, MS4, MS5, US3 and SR2. All these units have high levels of available K content (>125 ppm). The rest of the units have medium levels of available K. Regression analysis show that maize yield was significantly correlated with soil available K content ($r = 0.322$, $P < 0.01$, $n = 80$). This suggests that increasing soil available K is an effective practice to increase maize yield, especially in the areas where available K content is relatively low. However, correlation of maize yield with N-P-K compound application was not significant for the 2002 data, when the soil available K level was not considered.

4.3.2. Soil fertility evaluation using graphical approaches

A rapid method in soil test correlation was developed by Cate-Nelson (1965). This graphical method divides data into low and high probability of response groups and may produce results as satisfying as more complex regression models (Eckert, 1987). The main advantage of the Cate-Nelson approach is that it recognizes the basic limitation of soil tests: they are able only to separate the soils that are likely to respond to the added nutrient from those unlikely to respond. The simplicity of this approach has major practical advantages (Sanchez, 1976). The Cate-Nelson method has been widely used in the tropics. Similar methods were used to calibrate NO_3^- tests in several states throughout the Northeast and Midwest USA and suggested that when NO_3^- >20-25 ppm, additional dressing of N were unnecessary (Havlin *et al.*, 1999).

The critical level produced by the Cate-Nelson approach usually falls between medium and high levels of the category approach. The critical level of soil nutrients is specific to certain soil-crop situations. In Wang Jia Catchment and in terms of maize production, the critical levels for pH, total organic matter, total nitrogen, available nitrogen, available P and available K by the Cate-Nelson approach are likely to be ~6.5, 2.0%, 0.11%, 110 ppm, 11 ppm and 140 ppm, respectively. Those plots with soil data below these critical levels are more likely to give yield responses to relevant soil parameter increases (such as fertilizer application). Among these selected soil parameters, soil available P had the best correlation with maize yield, using the Cate-Nelson approach. This may mean that available P is a more important limiting factor than the others. The agricultural practice to increase soil available P (such as manure and P application) is likely to obtain maize yield responses in most plots. This confirmed the field observed

P-deficiency symptoms of purplish red leaves in maize. The result also indicates that Olsen-P originally developed for calcareous soils can also be used for acidic and neutral soils. Similar results were reported by Halvin *et al.* (1999). The critical value of 11 ppm available P falls in the high level category according to Chinese standards and medium level according to some reports (Halvin *et al.,* 1999).

4.3.3. Soil fertility evaluation using numerical approaches.

Soil fertility was evaluated to estimate maize yield using multiple regression models (Olsen and Olsen, 1986; Olsen *et al.,* 2001; Olsen and Lang, 2002). Norris (1971) used multivariate analysis to test if the variation of soil fertility can be characterized by the variation of a set of relatively few soil properties. Experimental results in Chungbuk Province, Korea, showed that 34.2% of the variability in dry weight of tobacco leaves was explained by soil chemical properties using multiple linear regression (Hong *et al.,* 2001). Stein *et al.* (1997) found a millet yield range of 0-2885 kg/ha, measured in 5 × 5m blocks. They were able to explain 30% of yield variability by multiple regression of soil variables. Gandah *et al.* (1998), used the same support size for yield sampling and explained only 5-28% of yield variability by regression. Groenigen *et al.* (2000) reported that different proportions of yield variability were explained by soil samples using different sampling strategies. In this study, soil data Set 4 collected in winter 1999 explained 32.8% of the variation of maize yield in 2000 (P <0.01, n = 79). By increasing the number of soil parameters, soil data Set 2 explained 74.4% of the variation of maize yield in 2000 (P <0.05, n = 20). After integrating the soil parameters into a soil fertility index for soil data Set 4, 16.9% of maize yield variability could be explained (P <0.001, n = 79). Meanwhile, soil fertility indices can directly indicate soil fertility status and are suitable for monitoring soil fertility and soil quality change.

Although soil parameters are important indicators of the current status of soil fertility, they are not in themselves useful indicators of sustainability. Changes in the indicators reflect the combined effects of land use. If the change in soil fertility parameters is positive and more is of better quality, then the soil can be regarded as improving in soil fertility. Conversely, if the trend line is negative, then soil fertility is decreasing. Calculating the slope of the trend is a way of quantifying change in soil fertility. A disadvantage of this approach is that it can be somewhat misleading if a soil is functioning at the highest quality attainable and cannot improve or conversely, if it is functioning at its lowest quality and cannot decrease further. Both cases show a static or no change trend, but are completely different. It is most desirable to show state of soil fertility on a normalized scale in addition to trends. In this study, the soil fertility index was calculated for soil fertility evaluation and for monitoring soil fertility change as a baseline. The concepts of Sun *et al.* (1995) for soil fertility index and Karlen and Stott (1994) for soil quality index were used. For each soil parameter, a scoring function (fuzzy approach) and threshold were established, mainly based on the literature. The scoring function for soil-specific parameter and specific-land use needs to be developed in the research region. Based on the selected soil parameters, soil fertility index was very variable from 0.277 for plot F4-3 in geounit US3 in the upper western interfluve to 0.999 in plots 2 and 3 in geounit LS2 at the catchment outlet. Consistent with the category approach, the relatively high soil fertility index values are located in the narrow plain along the stream or in the alluvial plain close to the village. Most of the lowest soil fertility index values belong to the soils in the upper west interfluve.

4.3.4. Intra-plot soil variability in terms of soil sampling strategy

Soil sampling methodology is a crucial issue for soil scientists (Havlin *et al.*, 1999). This issue was addressed by Mercer and Hall (1911) in their early fertility studies. Variability associated with collecting the sample is usually much greater than the variability associated with laboratory analyses. Reducing laboratory variability will usually have minimal effects on soil test recommendations (Mroz and Reed, 1991). The extent of soil variability is very site-specific (Cameron *et al.*, 1994; Mollitor *et al.*, 1980). Sabbe and Marx (1987) reported that recent farming and fertilizer applications complicated obtaining representative soil samples. Row crop and band-application fertilizers cause problems with soil sampling procedures (Kitchen *et al.*, 1990). Conservation tillage and fertilizer practices also increase variations of some soil fertility parameters in the field (Mallarino, 1996). In order to deal with this complicated situation, Dick and Thomas (1996) proposed categorizing soil sampling design as judgement sampling, simple random sampling, stratified random sampling, systematic sampling, composite sampling and stratified composite sampling. In practice, often only one composite sample is collected per field, regardless of field size and previous management history. Eash and Lamb (2002) found composite sampling resulted in fertilizer recommendations unrepresentative of the site, while the management zone method recommended the least fertilizer overall but most of it was applied in low testing areas. The same result was reported by van Groenigen *et al.* (2000).

Wang (2003) reported the limitation of current composite sampling strategy to interpret soil test data in Wang Jia Catchment. In this study, intra-plot soil samples were collected in a plot where organic manure and fertilizers of N, P and K were applied in sowing pits. Studies in the Exhaustion Land Experiment at Rothamsted showed that, with pH >6.0, P and K residues from inorganic fertilizers remained in forms available to plants for >50 years. This result was subsequently confirmed in the Hoosfield Barley Experiment, where P and K residues from 20 applications of farmyard manure were still available to plants after 100 years (Johnston and Powlson, 1994). Due to the residual effect, total soil organic matter, total nitrogen, available nitrogen, available phosphate and available potassium in pits were significantly higher than within inter-rows. The pH in pits was more neutral than inter-rows, due to the neutral pH of manure used (Wang, 2003). For most of the tested soil fertility parameters, pits had higher standard deviations than inter-rows, except for soil pH and available nitrogen. In terms of most soil fertility parameters, pits are significantly different from the composite sample, except for pH. These results suggest if composite samples were taken only from inter-rows, the results would have been similar, but the risk of sampling error would have been reduced. Eash and Lamb (2002) also noted that composite samples not avoiding areas with extremely high nutrient contents resulted in high soil P and K contents and therefore no further fertilizer application was indicated, even though crop nutrient deficiency symptoms were observed. Completely random sampling procedures for composite samples produced higher sampling variability under no-till banded phosphorus (Kitchen *et al.,* 1990).

4.4. Crop productivity

Besides soil fertility, crop yield is affected by factors such as climate, cultivar type and crop management. In the context of SHASEA project, the modified and innovative cultivation practices developed in the field experimental plots were incorporated into the sustainable land management plan and extended to the whole catchment. Therefore, it is important to evaluate these practices under field conditions in farmers' plots throughout the catchment. The relevant information summarized here not only provides a baseline for maize productivity in the catchment, but assists in evaluating and monitoring changes following introduction of modified and innovative cultivation practices at the catchment level.

4.4.1. Rainfall

Climatic information collected and stored in this information system included rainfall, air temperature, soil temperature, relative humidity, solar radiation, wind speed and wind direction. Focusing on maize production in the catchment, rainfall and temperature were used to explain some of maize productivity season by season differences. Weather is likely to be the biggest factor in season by season variations in maize yields.

Most crops growing in Wang Jia Catchment are rainfed. The annual rainfalls in 1999, 2000, 2001 and 2002 were 1028.7, 793.4, 857.8 and 759.6 mm, respectively. The rainfall data for 2001 and 2002 were incomplete. The amount of rainfall was relatively high in 1999 and low in 2000. There was an unexpected heavy hail storm (09 August 2001), which influenced final yields considerably due to the damaged leaves. Allowing for the incomplete record in the rainy season, August 2002 had the highest monthly rainfall among the four years. Maize yield was closely related to weather conditions and in the order of 2002 > 1999 > 2000> 2001.

Although the amount of water required for maize growth is enough from rainfall, the rainfall distribution is sporadic and unevenly spread over the cropping season. Most rain falls in the summer season from May to September, sometimes to October. The combined effect of low rainfall, low humidity and strong wind made the winter and early spring very dry. The lowest air relative humidity occurred in March or April depending on different years. The rainy season usually starts in May, but in abnormal years the rainfall comes late and can be delayed to June, which is a crucial period for seed germination and establishment. So in this area, soil moisture can be a seriously limiting factor for crop growth, particularly for the winter crop and early stage of summer crops. Soil moisture was reported as one of the key limiting factors affecting seed germination in dry environments (El-Sharkawi and Farghali, 1988; Potter *et al.*, 1986). The grain yields of maize can be reduced by early water deficits from 21% (Denmead and Shaw, 1960) to 48% (Barnes and Woolley, 1969). However, after the irrigation ponds were constructed in the catchment, they were not fully utilised, even in the relatively dry period, although irrigated plots with polythene mulch gave 23% higher yield than non-irrigated plots with the same treatment in the same catchment (Huang, 2001). Further studies are needed to explore the reasons for this lack of use of irrigation.

4.4.2. Temperature

Maize can germinate at relatively low temperatures of 10-15˚C (Blacklow, 1972), but growth is maximized at high temperatures (Hall and Ziska, 2000). The optimal soil temperature is 27.4˚C in the northern USA (Allmaras *et al.*, 1964) and 23˚C at 10 cm depth in central Iowa (Willis *et al.*, 1957). The monthly average air and soil temperatures at 15 cm depth in the catchment were similar and followed the same pattern for four years. From the weather data in 2002 from the Delta T-logger, the main air temperature and soil temperature at 15 cm at the seed germination stage (May) were 18.0˚C and 19.5˚C, respectively. In relation to the reported optimum temperature of 24˚C for maize seed germination (Purseglove, 1972), the local temperature was 5-6˚C lower than the optimum, but 5-6˚C higher than the 12˚C threshold needed for seed germination (Shun, 1997). During the vegetative growth stage, the mean values of air and soil temperature were ≤21.1˚C and ≤21.8˚C, which were still 5-6˚C lower than the optimum temperature of 26-27˚C (Allmaras *et al.*, 1964). These data suggest that an increase in soil temperature would increase maize growth. This may provide one of the possible explanations for the higher yield in the lower part of the catchment and in plots with polythene mulch.

There are major temperature variations in the catchment due to the large differences in elevation. The temperature difference could be as large as 5.2˚C in winter and 3.1˚C in summer. These differences can produce significant influences on crop growth and are likely to be one of the main reasons for maize yields in the order of lower part > middle part > upper part catchment. Unfortunately, these differences tend to be neglected in many catchment studies. Walker (1969) reported 20% seedling growth increase with a rise of 1˚C. Stone *et al.* (1999) found the grain yield increased by ~0.3 t/ha per 1˚C increase in average soil temperature across the range from 18.3˚C to 25.2˚C. Bollero *et al.* (1996) reported a 0.14 t/ha per 1˚C increase in average soil temperature. The intra-catchment temperature variation should be taken into account, especially when selecting crop cultivars. In this study, the recommended cultivar DF4 performed relatively well in the lower and middle catchment. However, it suffered late maturity problems in the upper catchment due to the lower cumulative temperature and did not appear to be suitable for the upper catchment, despite the fact that the altitude of the upper plots is lower than the 2200 m asl suggested as the highest altitude for DF4.

4.4.3. Maize cultivar

The introduction of cultivars with a high yield potential and the use of agrochemical inputs (herbicides, fungicides, pesticides) to protect that potential have appreciably increased maize yield. In this study, there were 13 cultivars recorded in 1999, eleven in 2000, four in 2001 and three in 2002. Among the three main cultivars, Q3 is a relatively old cultivar with high yield but low quality and is suitable only for animal feed. DF4 as a high yield cultivar was introduced to this catchment in 2000 by the SHASEA team. It has been adopted by more farmers since then. However, DF4 needs relatively high soil fertility and higher soil temperature than Q3 and HD4. This was reflected in a low average yield for DF4, compared to DH4 in 2000 and 2001, although the maximum yield of DF4 was higher than of HD4, meaning DF4 has a high yield potential. In 2002, when more attention was paid to cultivation techniques and DF4 was planted mostly in the lower and middle part, its average yield surpassed HD4. However, mean yields over four seasons showed no significant differences among the cultivars under field condition, when taking the catchment as a whole.

4.4.4. Contour cultivation

Contour cultivation was introduced into Wang Jia Catchment as a means to conserve soil and nutrients. It was reported as an easily operated and effective method (Huang, 2001). However, the effects of contour cultivation on erosion vary according to rainfall and slope (Milne, 2001). Huang (2001) reported that contour cultivation significantly increased crop yields according to the results from his field experimental plots in Wang Jia Catchment. However, results from the nearby experimental plots in the same catchment showed that there was no effect of contour cultivation on maize yield compared with downslope cultivation (Wang, 2003).

Although contour cultivation was not used primarily to improve maize yield in the catchment, observation on yield improvement have been analysed to monitor any additional benefits of this soil conservation practice. Under field conditions, maize yield did not show much advantage over contour cultivation, except for the 2002 survey. The general trend of maximum yield showed that contour cultivation had high yield potential. However, contour cultivation also had the minimum yield. The yield with contour cultivation was very variable when other factors affecting maize yield were not under control. In addition, it was difficult to judge the effect of contour and downslope cultivation because of the complexity of slope shape in the catchment. It was very often that part of the plot was cultivated along the contour, while the other part was downslope. The one-way ANOVA of mean yields over four years did not show significant differences. According to farmers' understanding, 84% plots in 2001 and 95% plots in 2002 adopted contour cultivation. Fujisaka (1993) reported that farmers are keen to learn about and apply conservation measures. They adapted or adopted conservation measures, as long as such methods are practical within their very limited resources and labour (Garrity, 1999). The tentative economic evaluation found that simply replacing downslope with contour cultivation improved economic return in Wang Jia Catchment (Wang, 2003). Whether the net return is sufficient for local farmers to adopt contour cultivation needs further socio-economic evaluation.

4.4.5. Polythene mulch

Clear polythene mulch allows solar radiation through to the soil and the heat trapped beneath the polythene then substantially increases soil temperature. Increased soil temperature with polythene mulch was reported by many researchers (Wang and Zhang, 1999; Lei *et al.*, 1994; Zhang *et al.*, 2000), especially at the time when soil temperature was relatively low, such as early spring or winter (Barton, 2000; Wang, 2003). Polythene mulch was also reported as conserving soil moisture (Zhang *et al.*, 2000; Lei et al., 1994). Therefore, Chen (1996), Wang (2003), Barton (2000) and Huang (2001) reported that polythene mulch increased maize yields. Polythene mulch has been extensively used for crops include cotton, maize, tobacco, juvenile rice, fruit tree seedlings, melons, vegetables and groundnuts as a means to maintain high soil temperatures, retain moisture and reduce weeds in China. However, polythene mulch may prevent rainfall penetration into the soil and then reduce soil moisture in certain circumstances (Wang, 2003) and increase runoff (Barton, 2000; Milne, 2001). Besides, continuous use of plastic film has negative environmental effects: "white pollution". Studies show that ~37.5 kg/ha plastic film remains in the soil when the land has been covered for more than three years. If the remaining plastic pieces weighed 45 kg/ha, the vegetable yield would decrease by 2-10% compared to no plastic coverage, probably due to influences on plant rooting and water movement in the soil profile (Li *et al.*, 1997). In this study, maize yield with polythene mulch was normally higher than without polythene mulch, except for 2001 when hail storms occurred. However, the one-way ANOVA of mean yield over four seasons showed no significant difference when taking the 100 plots as whole. This may have been due to the differences in other factors in these field conditions. More plots were cultivated with polythene mulch in

2002 when the plastic film was provided free. Thus, it is difficult to evaluate farmers' perception and adoption of polythene mulch due to administrative intervention. This is currently under further evaluation (M. Subedi, pers. comm., 2004).

4.4.6. Manure and fertilizers application

For centuries, the use of farm manure has been synonymous with successful and stable agriculture (Brady and Weil, 1999). One of the key features of Chinese traditional agriculture is the application of large amounts of farmyard manure (Gong *et al.,* 2000). Nowadays in China, manure application is still common agricultural practice in many crop systems. Reasonable manure application not only supplies organic matter and plant nutrients to the soil, but also prevents environment pollution from animal wastes. In Wang Jia Catchment, the manure application rate was normally lower than the rate recommended for high yields, which is 15,000 kg/ha, due to the shortage of manure sources in the village. Generally, high manure rates were applied to the plots close to the village in the middle and lower catchment; this may be due to the transportation problem, although it could also be applied to those plots further from the village in the upper part. The analysis of 2002 data showed that maize yield was significantly related to manure application. 14.9% of the variance of maize yield was coupled with variability in manure application ($r = 0.386$, $P < 0.001$, $n = 97$).

Following the same trend in the rest of China, chemical fertilizers used for maize production in the catchment were mainly N fertilizer as urea (only a few plots used ammonium bicarbonate), P fertilizer as single superphosphate and some NPK compound. To some extent, the fertilizer used depended on what farmers had in hand. The NPK compound was normally left from tobacco production, with a N-P_2O_5- K_2O content of 15-15-15. In terms of the number of plots and application rate, urea is the most common fertilizer followed by NPK compounds, then single superphosphate. Most plots received urea at ~675 kg/ha, which is the recommended rate. Although the single phosphate rate applied was low compared to the recommended rate (300 kg/ha), the combination rate of single superphosphate and compound was ~300 kg/ha (the P_2O_5 content of single superphosphate is normally 16-20%). Like the manure, the application rate of fertilizers also had a relationship with the location, especially the urea. Slightly more urea was applied in the lower and middle catchment. The analysis of 2002 data showed that 21.8 % of the variance of maize yield was explained by variability in manure and fertilizer applications ($r = 0.467$, $P < 0.01$, $n = 97$). Further regression of maize yield with each single variable showed that 10.7% of maize yield variance was explained by variability in urea application (r = 0.327, P <0.001, n = 97), while only 0.7% for NPK compound and none for single superphosphate (not significant, P = 0.426 and 0.876, respectively). These results indicate that N was the most deficient nutrient in the catchment. Manure and N fertilizer applications were highly effective in increasing maize yield.

4.5. Towards a generic protocol for land/soil information systems in subtropical highlands.

Data required for land information systems depend on the purposes of the system. Suitable data for agricultural land information systems may be derived from remote sensing, e.g. airphotos or/and satellite imagery; existing maps, especially soil and topographic maps; field observations and measurements, laboratory analyses and interviews with farmers. These data can be grouped into climate, topography, soil, crop and socio-economic information. Strategies for collecting data efficiently at different scales are crucial for data use and cost. This study commenced at the macro-scale, zoomed in to the meso-scale and finished at the microscale, as stated in Sections 4.1-4.4. This strategy provides a convenient framework for the selection of a representative catchment for detailed examination and also for rational extrapolation of obtained information, which may relate to limited locations. Focusing on limited locations allows more comprehensive data collection at each location without increasing cost.

4.5.1. Macro-scale: assessment of catchment representativeness at regional scale.

In order to extrapolate information to a larger scale, the information must be collected from a representative site. Logically, the existing documents, such as soil maps, topographical maps, airphotos and satellite images, can be used to select and evaluate site representativeness. These can provide a good understanding of the bio-physical context of the selected site. There have been numerous uses of remote sensing in resource assessment in recent years. The data reliability largely depends on the scale and interpretation of the images. In this study, topographical map and airphotos at 1:50,000 and satellite imagery with resolution of 20 m were satisfactory. They were used together to assess catchment representativeness using geomorphological criteria. Meanwhile satellite imagery was used in terms of land cover criteria. Both geomorphological features and land coverage are crucial in terms of agricultural land use and erosion control in this region.

4.5.2. Meso-scale: agro-environment assessment at catchment and plot scales.

To assess the agro-environment at the catchment scale, field surveys on geology, morphology, biology and pedology were carried out. The relevant maps of lithology and land cover and a synthetic geomorphopedologic sketch were produced using ILWIS and Arcview GIS software. Meanwhile data, such as climate, were collected and collated. Socio-economic data can be added in the future. These data can be used to explain the dynamic characteristics of the soil and crop production.

To assess crop production and to analyse effects of different agricultural practices, 100 plots were selected as reference plots in the catchment. These 100 plots were farmers' plots and were cultivated by farmers themselves. This approach allows information collected from real agricultural systems and encourages farmers' involvement. Crop yield, agricultural practices and soil fertility information were collected and analysed. This information helped to understand farmers' perception and adoption of recommended technologies and may generate some hints for future extension associated with the improved technologies.

For more detailed soil information, 30 plots were abstracted from the 100 plots. More soil parameters, such as mineralogy, CEC and texture, were analysed. The 100 plots are real agricultural plots, but there is a lack of control. In order to evaluate specific agricultural practice or land use, researches can be carried out under controlled conditions within the 30 plots. This approach balances agricultural reality and theoretical research and helps improved technologies to fit into local reality. These 30 plots will be kept as reference plots for monitoring effects of land use change in the future.

4.5.3. Micro-scale: intra-plot soil fertility variability assessement in a single plot.

To understand the intra-plot variability, a single plot was selected, where organic manure and N, P and K fertilizers were applied in sowing pits. Soil samples from pits and inter-rows were analysed for soil fertility parameters. This information can help to understand the effect of land management on soil variability and provide information for formulating sampling strategy for this specific land management.

4.6. Contributions of the investigation to the SHASEA Project

4.6.1 Co-operative nature of the SHASEA Project

As a multi-disciplinary research project, SHASEA involved an international research team from Belgium, China, Ireland, Thailand and the U.K. Five co-ordinated work packages were implemented and their inter-relationships are shown in Figure 4.1.

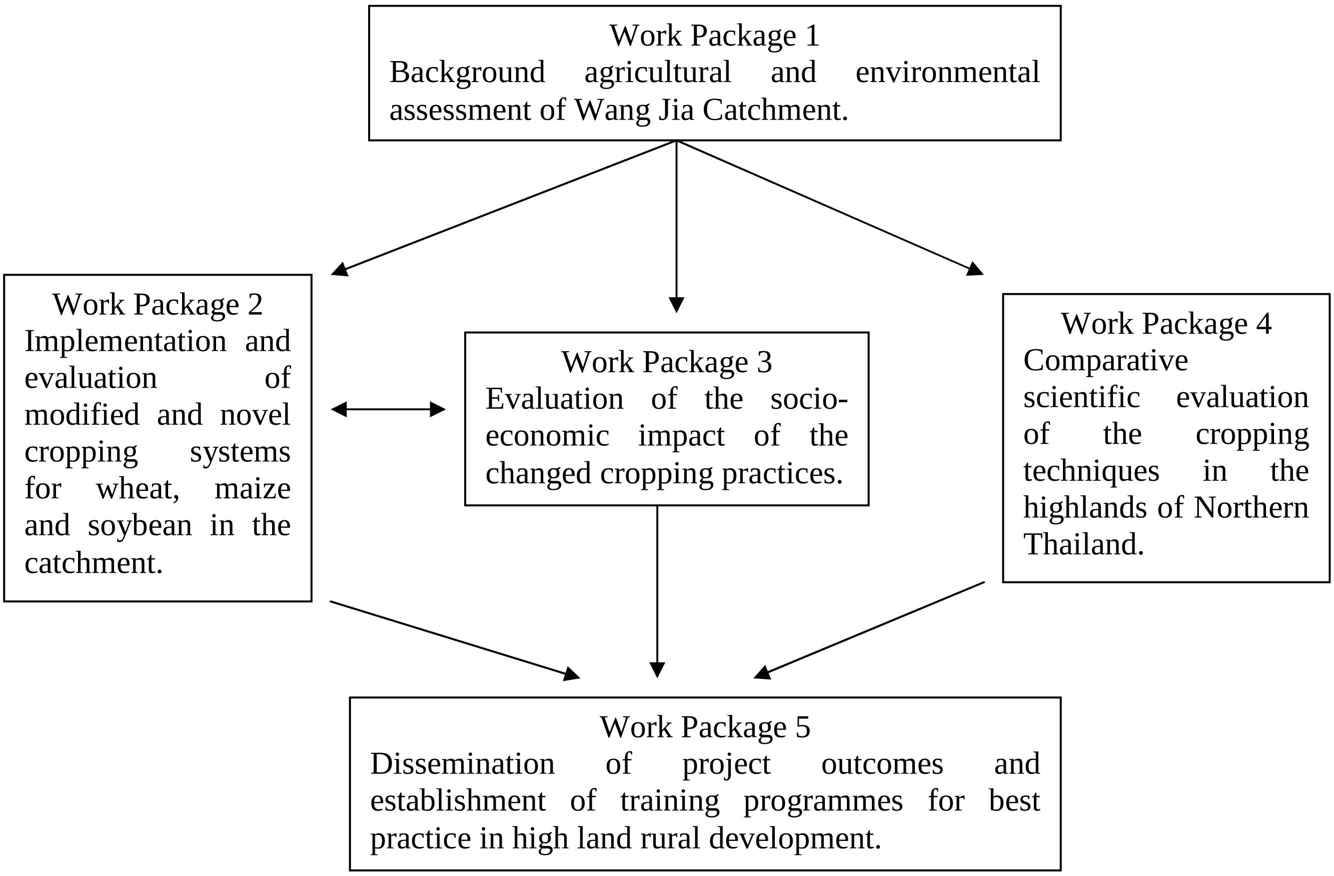


Figure 4.1. Five co-ordinated work packages and their inter-relationships in SHASEA (Source: http://www.wlv.ac.uk/science/environment/SHASEA/)

Work Package 1: The background agricultural and environmental assessment of Wang Jia Catchment was co-ordinated by Gembloux Agricultural University, Belgium. This work package involved a series of field surveys, laboratory analyses and remote sensing technology. The mineralogical analyses were carried out by the partner The Macaulay Land Use Research Institute, Aberdeen, U.K. The team evaluated both the regional external representativeness and internal variability of Wang Jia Catchment. The main outcome is this integrated land information system for humid subtropical highlands.

Work Package 2: Implementation and evaluation of modified and novel cropping systems for wheat, maize and soybean in the catchment was co-ordinated by Yunnan Agricultural University, China, with extensive contributions from the partner The Government of Kedu Township. Modified and novel cropping practices were evaluated both in field experimental plots and farmers' plots at the catchment scale. Land management changes were implemented in the catchment. The effects of these changes were investigated and need to be continually monitored in the future.

Work Package 3: Evaluation of the socio-economic impact of the changed cropping practices was co-ordinated by The National University of Ireland, Galway, Ireland. Preliminary cost-benefit analyses of the socio-economic impacts of the changed cropping practices were conducted. The extensive assessment included returns for stakeholders, poverty alleviation, income augmentation and rural development. These studies are being conducted by a Chinese Ph.D student.

Work Package 4: Comparative scientific evaluation of the cropping techniques in the highlands of northern Thailand was co-ordinated by Chiang Mai University, Thailand. The plot studies were carried out at the Pangmapa field station.

Work Package 5: Dissemination of project outcomes and establishment of training programmes for best practice in highland rural development was co-ordinated by the University of Wolverhampton, U.K. The project aims to disseminate information to the international research community, regional training agencies, local agricultural and conservation services and village communities.

4.6.2 The contributions of this Ph.D. study to the SHASEA Project

In accordance with the requirements of the SHASEA Consortium Agreement, this Ph.D. study was mainly involved in SHASEA work packages 1 and 2. However, the information system developed in this study was linked, using the 30 reference plots, with future socio-economic evaluation for selected agricultural practices and land use changes in work package 3. The land information system can also be integrated into SHASEA project webpages for information dissemination in work package 5. The contributions of this study to work packages 1 and 2 are shown in Figure 4.2.

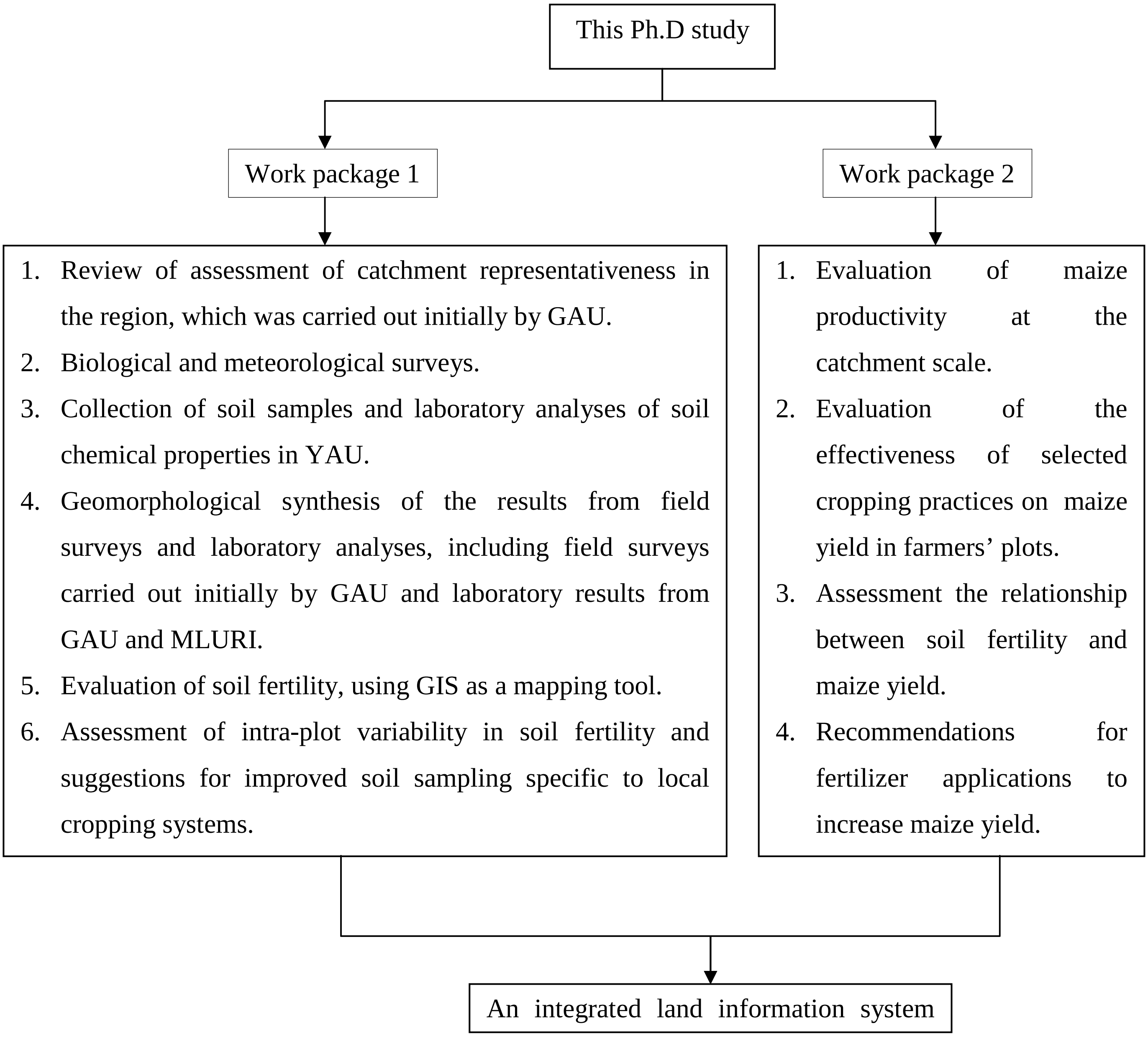


Figure 4.2. The contributions of the Ph.D. programme to work packages 1 and 2.

4.7. Limitations of the study

This study should be evaluated within the context of the SHASEA project of which it forms a contribution. As an integral component in two of the five work packages, this contributes to agricultural and environmental assessment in Wang Jia Catchment and to the implementation and evaluation of modified and novel cropping systems. This required facilities and expertise from different institutions and disciplines. Consequently, Gembloux Agricultural University, Yunnan Agricultural University, The University of Wolverhampton and The Macaulay Land Use Research Institute were involved. In addition, unlike the designed experimental plots, this study was carried out under field conditions with true farmers' plots and farmers' own management. Thus, some limitations were encountered during this study.

1. Soil was analysed in different laboratories with similar or different analytical methods. Different soil sample sets were analysed for different soil parameters. This means that soil data sets were not fully comparable and inter-set interpretation and referencing was problematic. Soil samples were not analysed in only one laboratory due to the limitation of facilities and also the collaborative nature of the SHASEA Project.
2. Some agrosystem information was collected via farmers' survey cards as an additional source of information. However, these data were semi-quantitative, because many farmers were semi-literate and it was not possible to completely track the cultivation history of all plots.
3. Under such field conditions with different land management practices in different and segmented plots owned by different farmers, it is impossible to find a suitable statistical method for the comparison and evaluation of the effects of different growth factors on maize productivity.
4. This study should have contributed to formulating land management policy in the catchment, if it was possible to be carried out before the SHASEA Project. Four years is insufficient to monitor land management change. However, this study provides the baseline for future monitoring.

4.8. Conclusions

The aims of this research were firstly to develop a land information system for the subtropical highland Wang Jia Catchment. This has been addressed in a series of surveys that are related both to agricultural land use and soil formation. The comprehensive surveys and description of the biophysical characteristics of the catchment were carried out during four years' work. The information system developed provides a baseline to assess subsequent change due to land management that aims at increasing crop productivity in a sustainable and environmentally-friendly way. The survey also established the representativity of the catchment in relation to the surrounding area and evaluated the adoption and effectiveness of the sustainable land management measures, developed from previous work at the catchment scale. All the original objectives for the study have largely been achieved. The general conclusions are as follows:

1. Wang Jia Catchment is a relatively representative catchment in the region by geomorphological and land cover criteria. Therefore, the land information developed from Wang Jia Catchment could be used as a reference system for similar catchments in the region.
2. Based on field surveys and laboratory analysis, a digital land information system has been developed using Arcview GIS. In the view of soil formation and agricultural production, this system includes data sets on climate, topography, geology, biota and soil characteristics. As a reference system for land use and cropping practice evaluation, this information could also serve to assist decision-making for sustainable agricultural land management and, in turn, contribute to poverty alleviation in the region. The protocol should be applicable in the subtropical region and the catchment details are representative for the local area. However, these need to be tested before a conclusive statement about general applicability can be made.
3. Most of the ~1000 mm annual rainfall fell in summer in Wang Jia Catchment. The annual mean air temperature was ~15°C with less seasonal difference. Under such climatic conditions, soils developed from residual, colluvial and alluvial materials of shale, dolomite and sandstone on different landscapes are still young and strongly influenced by their geological parent material. They are not the intensely weathered Ultisols as may have been expected in this region. Some 16 geomorphopedological units and five transition units were identified. Reconnaissance digital soil maps were produced using Arcview GIS.
4. Soils are normally slightly acidic to neutral. Soil fertility varies from poor to very fertile with most soil parameters ranging from low to high level according to China's national standards. Geounits in the flat or concave position (alluvial plain and catchment outlet) have relatively good soil fertility compared to the convex position or steep slopes (the interfluves). Meanwhile, the geounits close to the village tend to have good fertility compared to the geounits far from the village. By the Cate-Nelson approach, the critical values for maize production of pH, soil organic matter, total N and available N, P and K are 6.5, 2.0%, 0.11%, 110 ppm, 11 ppm and 140 ppm, respectively. These site and land use-specific thresholds could provide valuable information for fertilizer recommendation programmes in the region.
5. Maize yield was significantly correlated with soil pH, total N and available N, P and K. Regression of maize yield with soil fertility index had a R^2 value of 16.9% ($F = 15.64$, $P < 0.001$, $n = 79$). In 2002, 14.9% of the variance of maize yield was coupled

with variability in manure application ($r = 0.386$, $P < 0.001$, $n = 97$) and 10.7% coupled with variability in urea application ($r = 0.327$, $P < 0.001$, $n = 97$). Manure and N fertilizer applications were highly effective in increasing maize yield.

6. There was a considerable potential to increase maize yield with modified and innovative cropping practices, although the maize yield was relatively high in the catchment, compared to the Yunnan average. Maize yield was affected by rainfall and intra-catchment temperature differences. DF4 needs high soil fertility and temperature to realize high yield potential. Adopted primarily as a soil conservation practice, contour cultivation did not increase maize yield compared to downslope cultivation. Polythene mulch tended to increase maize yield in most years. These results largely accord with the results from controlled researcher-managed plots in the same catchment.
7. Due to the residual effect of manure and fertilizer applications, total soil organic matter, total nitrogen, available nitrogen, available phosphorus and available potassium in pits were significantly higher than that in inter-rows. The pH at pits was more neutral than the slightly acid inter-rows. For most of the tested soil fertility parameters, pits had higher standard deviations than inter-rows, except for soil pH and available nitrogen. In terms of most soil fertility parameters, pits are significantly different from composite samples, except for pH. These results suggest if composite samples were taken only from inter-rows, the results would have been similar but the risk of sampling error would have been reduced.

4.9. Suggestions for future research

Based on the findings and limitations, some suggestions are made for future research:

1. Adoption of modified and novel cropping practices are invariably influenced by economic considerations, social and institutional factors, often by existing legal land rights and sometimes by political constraints. Therefore, in addition to technical evaluation, socio-economic evaluation of these practices is crucial and in urgent demand for further evaluation on farmers' plots.
2. Soil physical parameters are crucial for soil fertility, land quality and agricultural sustainability evaluation and should be included in future research. These properties should include soil bulk density, water stable aggregates, field capacity and porosity.

3. In order to monitor the effects of land management change on agricultural sustainability, site-specific and key indicators need to be evaluated. The minimum data set for soil analysis, crop measurements and environmental factors were suggested. These sets must be responsive to the aims of the research. Sets should include the following soil parameters (pH, texture, structure and soil organic matter content). The salient crop parameters are crop yield and associated income generation. Instead of extensive and inconsistent data sets, carefully selected and consistent data sets will be more effective and efficient in monitoring land management change.
4. The land management plan was implemented in the catchment and surveys are imperative for the future monitoring. In order to make the monitoring more feasible and effective, surveys should focus on the 30 plots along with minimum data set.
5. Based on the findings from intra-plot soil fertility variations, a soil sampling strategy was proposed to decrease sampling error in the catchment. The proposed sampling strategy is to take replicate composite samples only from inter-rows. The relationship between crop growth and soil parameters from the suggested soil sampling strategy should be investigated.
6. In the SHASEA study, of which this project is a component, indigenous knowledge was taken into consideration in the formulation of land management strategies. This approach should be increasingly developed in the future, along with adoption of participatory approaches.
7. This project has established a land information system suitable for similar catchments in the region. There is considerable potential, both for further development of this system and also to apply this system in the formulation of sustainable land management plans in highland catchments.

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Appendix 1. Chemical properties of composite soil samples collected in February 1999, adapted from Baire and Ghuisoland (2001).

Plot	pH	Ex. Acidity (meq/100g)	Ex. Al^{+++} (meq/100g)	$CaCO_3$ (%)	Organic C (%)	Organic N (%)	Ca^{++} (meq/100g)	Mg^{++} (meq/100g)	K^{+} (meq/100g)	Total Cation (meq/100g)	Eff. CEC (meq/100g)	Available. P (mg/ 100g)	Mn (mg/ 100g)	Zn (mg/ 100g)
1.1	5.5	1.4	1.2	-	1.9	0.15	2.97	2.30	0.52	5.78	7.18	2.1	60.2	1.2
1.2	6.0	0.5	0.3	-	1.3	0.11	6.08	1.77	0.26	8.12	8.62	2.1	116.2	0.9
2.1	7.8	-	-	4.1	2.3	0.20	18.49	8.66	0.20	27.36	-	4.2	570.7	2.5
2.2	6.0	0.4	0.1	-	1.6	0.13	6.29	2.59	0.21	9.10	9.45	3.4	209.1	1.6
2.3	5.6	0.4	0.1	-	1.1	0.13	8.19	2.34	0.19	10.72	11.09	1.8	81.6	0.8
2.4	5.8	0.2	0.0	-	1.7	0.14	7.08	1.67	0.27	9.02	9.22	3.4	232.5	1.2
2.5	6.5	-	-	-	1.5	0.13	8.97	2.76	0.43	12.17	12.17	4.7	138	1.9
3.1	6.4	0.2	0.0	-	1.3	0.15	6.48	1.36	0.25	8.08	8.10	3.0	169.1	2.4
3.2	7.3	-	-	-	1.4	0.14	8.80	2.54	0.28	11.63	-	1.8	237.1	1.9
3.3	7.7	-	-	0.2	1.2	0.12	7.72	2.66	0.19	10.57	-	1.4	194.1	1.3
4.1	5.6	0.8	0.4	-	1.2	0.11	2.30	1.12	0.30	3.72	4.47	5.0	22.8	0.8
4.2	4.9	1.8	1.1	-	0.8	0.09	1.39	0.66	0.15	2.19	3.94	0.9	49	0.5
4.3	5.5	0.3	0.3	-	0.9	0.10	3.37	2.03	0.25	5.65	5.93	1.2	163.9	0.9
4.4	5.6	0.3	0.1	-	1.0	0.08	2.59	1.16	0.23	3.99	4.24	2.2	89.9	0.7
7.1	5.7	0.2	0.1	-	1.7	0.16	57.40	4.26	0.22	61.88	62.08	2.8	327	2.2
7.2	6.9	-	-	-	1.6	0.14	28.32	2.02	0.19	30.54	30.54	4.8	429	2.3
7.3	8.0	-	-	1.1	1.5	0.13	54.50	3.09	0.27	57.87	-	2.8	317.7	2.1
8.1	5.5	0.4	0.3	-	1.7	0.13	6.03	2.11	0.60	8.74	9.14	0.9	100.2	1.1
8.2	6.8	-	-	-	1.5	0.12	36.07	3.51	0.36	39.93	39.93	1.1	292.7	1.1
8.3	7.7	-	-	4.0	1.1	0.10	17.62	13.31	0.31	31.24	-	1.2	695.7	1.9
9.1	5.3	0.5	0.4	-	1.3	0.11	3.77	1.56	0.59	5.91	6.38	1.2	108	0.9
9.2	5.0	1.8	1.2	-	1.4	0.14	3.17	1.09	0.50	4.75	6.55	1.4	41	0.8
9.3	5.6	0.3	0.1	-	1.9	0.14	5.43	2.01	0.47	7.90	8.20	0.8	139.9	1.4
10.1	6.5	0.2	0.0	-	1.7	0.15	7.62	1.85	0.56	10.03	10.23	7.0	169	2.4
10.2	7.5	-	-	-	1.9	0.15	11.93	2.59	0.43	14.95	14.95	12.6	262.9	4.2
10.3	7.7	-	-	1.7	1.9	0.17	62.57	4.11	0.58	67.26	-	13.1	426	4.7
10.4	8.0	-	-	7.3	2.8	0.27	112.35	6.30	1.17	119.82	-	6.8	89.5	8.5
11.1	7.8	-	-	3.8	1.7	0.15	19.76	10.10	0.38	30.24	-	0.9	334	1.2
11.2	5.6	0.2	0.0	-	1.7	0.14	4.43	1.88	0.55	6.86	7.06	2.3	96	1.5
11.3	5.7	0.5	0.2	-	1.1	0.09	2.99	1.60	0.60	5.20	5.70	1.1	30	1
12.1	7.3	-	-	-	1.2	0.10	95.50	5.81	0.37	101.69	101.69	0.9	445.2	1.1
12.2	8.0	-	-	3.3	1.3	0.17	23.43	5.02	0.40	28.85	-	2.1	134.5	1.6
12.3	6.1	0.2	0.0	-	2.1	0.16	5.07	1.72	0.72	7.50	-	0.5	153.5	1.4
13.1	7.8	-	-	1.4	3.9	0.34	25.30	6.47	0.52	32.29	-	5.8	449.5	6.6
13.2	8.1	-	-	4.0	2.5	0.21	33.03	6.28	0.19	39.50	-	2.2	334.4	2.6
13.3	7.0	-	-	-	2.9	0.27	211.53	5.04	0.37	216.93	-	2.8	131.1	2.4

Appendix 2. Chemical properties of soil samples collected from 100 plots in December 1999.

Plot	pH	Organic Carbon (%)	Organic Matter (%)	Total N (%)	Available N (ppm)	Available P (ppm)	Available K (ppm)
1	7.2	1.59	2.74	0.16	96	18.41	148
2	7.8	2.39	4.13	0.21	139	31.00	192
3	6.9	1.77	3.06	0.18	113	21.05	174
4	7.3	1.43	2.47	0.14	110	11.09	158
5	7.1	1.27	2.19	0.12	88	4.05	153
6	7.3	1.48	2.56	0.13	96	4.64	125
7	6.9	1.20	2.07	0.11	72	2.89	140
8	7.1	1.41	2.42	0.15	79	11.09	80
9	7.3	1.98	3.41	0.19	125	7.87	111
10	7.2	1.71	2.94	0.16	104	2.89	93
11	7.2	1.43	2.47	0.14	88	3.18	180
12	NA	1.62	2.80	0.16	118	4.94	170
13	6.3	1.46	2.52	0.15	109	5.23	102
14	5.6	1.43	2.39	0.15	96	7.87	153
15	5.4	1.46	2.52	0.15	118	9.77	145
16	6.0	1.31	2.25	0.14	111	11.09	68
17	5.7	1.96	3.38	0.14	104	7.87	71
18	7.2	1.11	1.92	0.13	85	7.87	107
19	5.7	1.18	2.03	0.11	108	9.33	235
20	6.4	2.00	3.45	0.17	139	10.65	184
21	5.5	1.74	3.00	0.15	137	4.06	168
22	6.9	1.57	2.71	0.14	104	0.84	132
23	6.3	1.45	2.50	0.11	127	0.84	100
24	5.2	1.05	1.81	0.09	104	9.62	82
25	6.2	1.07	1.85	0.11	103	2.01	80
26	6.8	1.33	2.28	0.13	120	3.77	142
27	6.9	1.59	2.75	0.13	120	0.84	70
28	7.3	1.11	1.91	0.11	136	0.54	113
29	5.5	0.87	1.49	0.10	91	2.30	162
30	6.7	1.09	1.88	0.09	117	2.89	104
31	6.8	1.03	1.78	0.11	76	3.77	120
32	6.7	1.15	1.98	0.12	66	0.84	173
33	6.4	1.27	2.19	0.12	92	0.54	151
34	6.9	0.98	1.70	0.10	72	0.54	116
35	7.1	1.18	2.04	0.12	101	2.01	130
36	6.0	1.13	1.95	0.11	113	0.54	93
37	5.7	0.75	1.30	0.08	80	2.01	115
38	5.5	1.13	1.95	0.10	118	3.18	150
39	5.5	1.27	2.19	0.11	96	7.87	110
40	6.4	0.94	1.61	0.09	95	2.01	152
41	5.5	1.06	1.83	0.10	112	3.47	235
42	7.1	1.36	2.35	0.13	85	9.62	206
43	6.9	1.20	2.07	0.11	116	0.54	177
44	6.0	1.04	1.80	0.11	93	3.77	176
45	5.5	1.17	2.01	0.11	109	5.09	252
46	7.0	1.03	1.78	0.10	101	3.77	118
47	6.4	1.11	1.92	0.10	107	0.54	153

48	7.4	1.17	2.01	0.11	84	0.54	140
49	7.6	2.71	4.67	0.25	263	54.73	388
50	6.4	1.44	2.47	0.13	116	5.09	157
51	5.6	1.66	2.86	0.15	144	6.69	178
52	6.2	1.04	1.80	0.10	107	0.84	195
53	5.2	0.86	1.48	0.07	94	2.59	169
54	5.4	0.86	1.49	0.09	102	3.47	193
55	5.3	0.93	1.60	0.09	92	3.92	106
56	5.3	0.89	1.54	0.09	105	3.47	191
57	5.2	1.13	1.94	0.11	120	7.57	200
59	5.7	1.05	1.80	0.09	108	2.89	109
60	5.3	0.74	1.29	0.08	69	1.57	222
61	6.0	1.06	1.83	0.10	112	0.54	140
62	6.5	0.84	1.46	0.09	54	4.06	65
63	6.3	1.17	2.01	0.09	75	3.77	177
64	5.5	0.98	1.69	0.10	76	7.57	132
65	5.7	0.62	1.07	0.07	72	1.57	114
66	5.6	1.02	1.76	0.08	77	9.62	142
67	6.7	1.08	1.87	0.11	125	5.82	147
68	6.2	0.87	1.49	0.10	66	0.54	74
69	6.9	0.71	1.22	0.07	51	4.64	107
70	7.8	2.77	4.77	0.24	197	2.74	105
71	7.8	1.13	1.95	0.11	97	3.47	74
72	6.7	1.21	2.09	0.11	105	3.47	86
F1-1	5.6	2.73	4.71	0.17	205	16.65	161
F1-2	5.4	1.93	3.34	0.15	109	21.05	98
F2-1	5.3	0.46	0.80	0.12	97	21.05	83
F2-2	5.7	1.35	2.32	0.16	235	4.94	72
F2-3	5.8	1.34	2.31	0.15	229	7.72	111
F3-1	6.0	1.10	1.89	0.13	94	9.33	106
F3-2	7.5	0.79	1.36	0.11	145	4.94	90
F3-3	7.7	1.74	3.00	0.18	138	13.43	112
F4-1	6.6	1.07	1.84	0.12	134	3.47	138
F4-2	5.7	1.07	1.84	0.13	118	6.99	141
F4-3	5.6	0.67	1.15	0.08	77	3.77	78
F4-4	5.7	0.57	0.97	0.11	93	3.77	128
F7-1	7.6	1.59	2.74	0.17	191	8.16	100
F7-2	7.1	1.25	2.16	0.15	159	1.72	98
F7-3	7.2	1.19	2.06	0.14	156	19.73	114
F9-1	5.4	0.92	1.58	0.11	94	0.84	178
F9-2	5.3	1.10	1.89	0.13	180	23.68	194
F9-3	5.6	1.14	1.97	0.13	145	2.01	162
F10-1	6.9	1.54	2.65	0.16	164	21.05	183
F10-2	6.8	1.37	2.36	0.16	108	9.71	207
F10-3	8.0	1.77	3.05	0.21	163	23.68	157
F11-1	7.2	1.00	1.72	0.12	126	0.54	155
F11-2	7.0	1.19	2.05	0.14	113	9.33	136
F11-3	6.4	0.93	1.60	0.12	149	10.50	75
F12-1	6.8	1.19	2.06	0.13	148	3.91	158
F12-2	5.5	1.11	1.91	0.13	144	18.12	205
F12-3	6.1	1.09	1.88	0.13	157	4.64	104

NA = Not available.

Appendix 3. Chemical properties of soil samples collected from 30 plots in October 2001.

Plot	pH	Organic C (%)	Organic Matter (%)	Total N (%)	Total P (%)	Total K (%)	Available N (ppm)	Available P (ppm)	Available K (ppm)
F1-1	4.7	2.21	3.82	0.17	0.09	1.44	128	16	164
F1-2	5.1	1.24	2.08	0.11	0.07	1.78	58	32	66
F2-1	4.5	1.54	2.66	0.16	0.09	1.79	93	40	79
F2-2	5.3	1.82	3.12	0.19	0.11	2.56	118	10	68
F2-3	5.0	1.59	2.73	0.18	0.07	2.47	99	19	111
F3-1	4.8	1.31	2.25	0.14	0.07	2.44	84	23	95
F3-2	7.1	1.14	1.99	0.12	0.05	2.50	52	16	106
F3-3	7.6	1.90	3.23	0.19	0.07	2.52	97	19	82
F4-1	6.1	1.18	2.04	0.11	0.04	1.93	52	8	108
F4-2	5.6	1.39	2.59	0.13	0.05	3.08	64	20	130
F4-3	5.1	1.03	1.75	0.12	0.04	2.74	87	10	78
F4-4	4.9	0.70	1.23	0.10	0.04	2.52	50	18	119
F7-1	7.5	1.96	3.36	0.10	0.07	2.60	106	19	89
F7-2	6.3	1.57	2.71	0.15	0.14	3.66	116	23	118
F7-3	7.1	1.41	2.45	0.16	0.06	2.65	84	24	89
F8-1	4.9	1.30	2.21	0.12	0.05	1.13	95	14	125
F8-2	5.7	1.18	2.04	0.11	0.04	2.25	73	14	124
F8-3	5.9	1.18	2.06	0.12	0.05	2.32	99	8	131
F9-1	5.0	1.09	1.79	0.11	0.06	2.56	71	17	141
F9-2	5.0	1.46	2.60	0.15	0.07	2.68	105	25	179
F9-3	5.6	1.70	3.00	0.15	0.06	2.23	113	10	176
F10-1	6.9	1.96	3.34	0.20	0.10	3.67	111	43	207
F10-2	5.5	1.79	3.12	0.11	0.09	4.01	59	24	155
F10-3	7.7	2.19	3.80	0.20	0.11	2.91	135	36	158
F11-1	7.8	1.33	2.30	0.15	0.07	1.87	93	16	160
F11-2	7.0	1.24	2.12	0.12	0.07	4.64	61	27	97
F11-3	6.1	1.30	2.20	0.29	0.08	3.83	156	19	268
F12-1	8.0	1.77	3.05	0.18	0.09	3.78	65	20	136
F12-2	5.8	1.61	2.77	0.15	0.10	4.36	74	17	134
F12-3	5.8	1.53	2.65	0.12	0.11	4.30	96	30	167

Appendix 4. Chemical properties of soil samples collected from 30 plots in April 2002.

Plot	pH	Organic C (%)	Organic Matter (%)	Total N (%)	Available N (ppm)	Available P (ppm)	Available K (ppm)
F2-1	5.47	1.32	2.28	0.15	66.89	41.98	90.53
F2-2	6.16	1.84	3.17	0.19	110.98	22.44	78.58
F2-3	5.84	1.76	3.03	0.20	156.59	20.30	118.73
F3-1	8.48	1.34	2.23	0.13	65.37	25.21	85.06
F3-2	8.48	1.16	1.96	0.12	64.61	19.42	99.50
F3-3	8.64	1.88	3.34	0.19	113.26	20.67	89.46
F4-1	6.95	1.38	2.36	0.13	67.65	10.37	129.59
F4-2	6.18	1.42	2.43	0.15	69.93	21.29	190.14
F4-3	5.80	1.03	1.77	0.11	59.29	9.67	78.82
F4-4	5.95	0.82	1.40	0.08	43.33	25.45	130.08
F7-1	8.58	1.89	3.28	0.17	94.26	15.39	77.23
F7-2	7.79	1.98	3.19	0.19	110.98	33.62	145.08
F7-4	7.97	1.56	2.68	0.14	64.61	17.50	83.92
F8-1	5.52	1.26	2.18	0.14	63.85	9.37	154.57
F8-2	5.67	1.27	2.24	0.11	60.81	8.75	120.20
F8-3	6.39	1.24	2.17	0.14	68.41	7.67	132.79
F9-1	5.41	1.39	2.61	0.13	64.61	13.67	123.70
F9-2	5.61	1.60	2.71	0.16	95.02	47.91	275.70
F9-3	6.20	1.71	3.24	0.16	73.73	41.59	192.58
F10-1	7.26	1.91	3.24	0.19	114.02	37.19	190.76
F10-2	6.44	1.85	3.17	0.20	141.38	27.67	166.69
F10-3	8.84	2.26	3.99	0.25	185.47	39.98	132.29
F11-1	8.16	1.29	2.27	0.17	85.89	7.76	134.57
F11-2	7.19	1.56	3.02	0.14	90.46	25.12	122.95
F11-3	6.52	1.26	2.28	0.13	105.66	17.81	229.21
F12-1	7.42	1.63	2.74	0.17	137.58	1.28	129.69
F12-2	5.85	1.38	2.29	0.15	117.06	33.16	164.84
F12-3	6.19	1.64	2.77	0.16	138.34	14.55	138.90

Appendix 5. Chemical properties of soil samples collected in October 2001 for intra-plot comparison.

Sampling	pH	Organic matter (%)	Total N (%)	Available N (ppm)	Available P (ppm)	Available K (ppm)
pit1	5.61	20.24	1.58	120	19.37	144
pit2	6.10	18.70	2.32	107	30.68	171
pit3	5.80	19.37	1.88	109	23.29	149
pit4	5.80	17.91	0.23	105	24.93	131
pit5	5.87	17.75	1.67	109	17.66	102
pit6	5.95	20.86	1.76	140	31.68	124
pit7	5.58	16.31	1.78	97	16.65	120
pit8	4.93	18.95	2.06	113	50.15	156
pit9	5.46	19.13	1.96	117	25.47	180
pit10	5.72	14.65	1.70	116	28.97	130
inter1	5.31	11.93	1.30	81	13.70	65
inter2	5.68	11.13	1.33	71	10.04	72
inter3	5.76	12.85	1.30	96	21.94	76
inter4	4.58	12.69	1.27	96	13.02	70
inter5	5.22	13.41	1.25	--	20.73	81
inter6	5.39	11.62	0.50	78	12.84	77
inter7	4.74	8.91	0.96	93	8.71	64
inter8	4.59	10.92	1.21	138	12.71	73
inter9	4.88	10.21	1.14	52	13.48	89
inter10	5.52	11.58	1.06	62	10.92	64
Composite	5.70	12.41	1.19	62	12.54	80

Appendix 6. Field measurements of maize yield in 1999.

Plot No	Maize cultivar	Planting direction	Double row	Intercrop	Polythene mulch	Winter crop	Plant space (m)	Row space (m)	Grain yield at 13% moisture (kg/ha)
1	Q3	Down	Yes		No	Vegetable	0.40	0.55	-
2	old	Contour	No		N	Wheat	0.53	0.61	5800
3	DH3	C	Y		N	Wheat	0.35	0.53	7000
4	HD4	D	Y	Soybean	N	Pea	0.40	0.94	-
5	OLD+Q3	C	N		N	Pea	0.46	0.56	5100
6	HD4+YD	D	Y	Sunflower	N	Pea	0.33	0.54	4960
7	HD2	D	Y		N	Pea	0.36	0.57	6880
8	Q3	D	Y		N	Wheat	0.37	0.66	7740
9	HD4	D	Y		N	Pea	0.33	0.53	7780
10	HD4	C	N	Pumpkin	N	Pea	0.72	0.86	1920
11	Q3	D	Y	Frenchbean	Yes	Pea	0.46	0.69	7360
12	Q3	D	Y	Soybean	N	Pea	0.39	0.79	5660
13	HD4	C	Y	Soybean	N	Pea	0.45	1.03	4540
14	HD4	C	N	Frenchbean	N	Pea	0.54	0.61	4460
15	HD4	C	Y	Soybean	N	Pea	0.46	0.72	4860
16	HD4	C	Y	Frenchbean+Sunflower	N	Pea	0.57	0.94	5000
17	Q3	C	Y	Frenchbean	N	Pea	0.37	1.24	-
18		C	Y	Soybean	N	Pea	0.55	0.83	4240
19	DH132	D			N	Pea	0.53	0.57	4760
20	HD4	D	Y	Chestnut	N	Wheat	0.49	0.58	-
21	OLD	C			N	Pea	0.50	1.09	4324
22	Q3	C	Y	Chestnut	N	Wheat	0.42	0.77	6840
23	Q3	C	N		N	Wheat	0.45	0.59	9040
24	HHD4	C	N		N	Pea	0.56	0.49	2787
25	HHD4	C	Y	Soybean	N	Pea	0.51	0.95	2360
26	OLD	C	Y	Frenchbean	N	Pea	0.46	0.73	3250
27	HHD4	C	N	Pumpkin	Y	Pea	0.44	0.78	6952
28	DH4	C	N		Y	Wheat	0.40	0.83	3619
29	Q3	D	Y	Soybean	N	Pea	0.44	0.67	7300
30	OLD	D	Y	Frenchbean	N	Pea	0.50	0.70	4182
31	Q3	D	Y	Frenchbean +Pumpkin	N	Pea	0.41	0.76	2800
32	Q3	C	Y	Soybean	N	Wheat	0.41	0.77	4324
33	Q3	D	Y	Frenchbean	Y	Pea	0.34	0.68	4400
34	Q3	D	Y	Frenchbean	N	Pea	0.42	0.93	6120
35	DH132	C	N		N	Fallow	0.49	0.64	-
36	YD	C	N	Soybean	N	Fallow	0.44	0.97	3100
37	Q3	C	N		N	Wheat	0.51	0.66	5100
38	Q3	D	Y	Soybean and Sunflower	N	Wheat	0.34	0.98	5848
39	HD2	C	Y	Chestnut+Soybean	N	Wheat	0.28	0.75	5700
40	Q3	C		Sunflower	N	Wheat	0.40	0.66	3905
41	Q3	C	Y	Frenchbean	N	Wheat	0.36	0.58	7940
42	OLD	D	Y		N	pea	0.42	0.53	6280
43	Q3	D	N	Sunflower	N	Wheat	0.37	0.65	7100
44	Q3	C	Y	Chestnut	Y	Pea	0.42	0.53	7880
45	DH132	C	Y	Frenchbean	N	Wheat	0.41	0.61	5524
46	Q3	D	Y		Y	Pea	0.38	0.63	6000
47	Q3	D	Y		N	Pea	0.41	0.72	4020
48	Q3	D	N	Frenchbean +Pumpkin	N	Wasteland	0.41	0.51	3905

49	DH132	D	N		N	Wheat	0.38	0.64	-
50	DH132	D		Chestnut	N	Pea	0.45	0.62	-
51	DH132	SD	Y	Chestnut+Soybean	N	Pea	0.45	0.71	-
52	OLD	D	Y	hestnut+Frenchbean	N	Pea	0.36	0.67	4644
53	LD2	C	Y	Sunflower	Y	Pea	0.36	0.54	5320
54	HD2	D	Y	Frenchbean	Y	Pea	0.35	0.78	5400
55		D	Y	Frenchbean	N	Pea	0.40	0.83	5960
56		D	Y		N	Pea	0.28	0.65	7160
57	Q3	D	Y	Chestnut	N	Wheat	0.34	0.58	6000
59	HD4	C	N		N	Pea	0.51	0.61	4880
60	Q3	C	N	Pumpkin	N	Pea	0.43	0.53	5080
61	DH132	D	Y		N	Pea	0.52	0.59	4040
62	HD4	C	Y	Soybean	N	Pea	0.38	0.93	3600
63	HD4	C	N		Y	Wheat	0.37	0.72	6160
64	HD4	D	Y	Sunflower	Y	pea	0.30	0.50	-
65	Q3+HD4	C	N		N	pea	0.34	0.71	-
66		C	N		N	pea	0.36	0.59	4680
67	DH132	C	N	Soybean	N	pea	0.84	0.99	3920
68	Q3	C	N	Soybean	N	pea	0.43	0.97	6000
69	DH132	D	Y		N	pea	0.49	0.64	5900
70	Q3	D	Y	Frenchbean	N	pea	0.52	0.77	5540
71	HD2+HD4	C	Y	Sunflower	N	pea	0.38	0.59	3340
72	Q3	C	N		N	pea	0.60	0.72	3800
F2-1	Q3	C	Y	Soybean	N	pea	0.47	0.60	5460
F2-2	Q3	D	Y	Soybean	N	pea	0.45	0.78	6900
F2-3	Q3	C	N		N	pea	0.43	0.65	7080
F3-1	HD4	C	Y		N	pea	0.47	0.63	5120
F3-2	HD4	D	Y		Y	pea	0.31	0.57	4080
F3-3	HD4	C	N		N	pea	0.46	0.56	7840
F4-1	HD4	C	Y		Y	pea	0.36	0.56	5840
F4-2	HD4	D	Y		N	pea	0.50	0.64	6580
F4-3	Q3	D	Y		Y	pea	0.31	0.59	-
F4-4	Q3	D	Y		Y	pea	0.27	0.60	6040
F7-1	HD4	D	Y	Soybean	N	pea	0.35	0.58	7940
F7-2	HD4	D	Y		N	pea	0.37	0.59	7180
F7-3	HD4	D	Y		N	pea	0.33	0.53	8260
F9-1	Q3	C	Y	Frenchbean	N	Wheat	0.43	0.87	2500
F9-2	HD4+LD	C	N	Chestnut	N	pea	0.44	0.55	4680
F9-3	Q3	C	Y	Chestnut+Frenchbean	N	Wheat	0.37	0.61	5940
F10-1	HD2	D	N	Soybean	N	pea	0.41	0.64	5053
F10-2	LD1	C	Y		Y	Wheat	0.50	0.57	-
F10-3	LD1	D	Y		N	pea	0.42	0.51	-
F11-1	DH132	D	Y	Soybean	Y	pea	0.33	0.75	5440
F11-2	LD1	C			N	pea	0.48	0.57	3140
F11-3	HD4	D	Y		Y	pea	0.41	0.60	-
F12-1	YD13	C		Chestnut	N	pea	0.45	0.64	4680
F12-2	YD13	D	Y	Soybean+Pumpkin	N	Wheat	0.44	0.63	7667
F12-3	Q3	C	N	Chestnut	N	pea	0.44	0.59	-

Appendix 7. Field measurements of maize yield in 2000.

Plot No	Maize cultivar	Plant space (cm)	Row space (cm)	Planting direction	Double rows	Intercrop	Polythene mulch	Grain yield at 13% moisture (kg/ha)
1	Q3	50	63	Down	No			6825
2	Old	34	48	Contour	Yes			6507
3	HD4	35	55	D	Y			6297
4	Tobacco	31	89	C	Y			
5	DF4	51	70	D	Y			5867
6	HD4	35	49	D	Y			5825
7	HD2	28	77	D	N			4678
8		45	65	D	Y			5487
9	Q3	34	61	D	Y			5078
10	YD	39	69	D	Y		Y	5289
11	HD4	45	65	D	Y		Y	6882
12	DF4	38	78	D	Y	Soybean		3226
13	DF4	33	107	D	Y	Soybean	Y	3157
14	HD4	58	69	D	Y			2395
15	HD4	41	90	C	Y			4432
16	HD4	29	56	D	Y		Y	6101
17	DF4	33	114	C	Y	Soybean		1780
18	Q3	31	43	D	Y			5635
19	Maize							
20	Maize							
21	Q3	40	92	D	Y	Soybean		5694
22	HD	43	68	D	Y	Soybean Sunflower		5111
23	HD	39	63	D	Y			5630
24	DF4	59	60	C	N			2512
25	Chili							
26	DF4	35	69	D	Y			7739
27	DF4	43	84	D	N			4583
28	DF4	38	80	D	N			3629
29	DF4	41	86	D	Y			6533
30	LD	41	69	D	Y			4615
31		35	66	D	Y			3086
32	Q3	36	60	C	Y			7854
33	DF4	39	70	D	Y		Y	7014
34	HD	130	78	D	Y	Soybean Sunflower chestnut		3550
35	HD	70	53	D	N			1608
36	HD	41	48	D	N			2863
37	DF4	43	77	C	N	Frenchbean		3240
38	DF4	41	63	D	Y			6234
39	Q3	51	44	C	N			2525
40	Q3	41	63	D	Y	Chestnut		3024
41		34	68	D	Y			
42	HD	33	45	D	Y			6496
43	HD	38	48	D	Y			5714
44	HD	40	73	C	N	Sunflower		4952
45		48	68	C	Y			3770
46	HD	43	71	D	Y		Y	6137
47	DF4	44	80	D	Y			2910
48	Waste land							
49	Tobacco							
50	DF4	40	51	D	N			6316
51	DF4	44	55	SD	N			6000
52		42	68	D	Y	Frenchbean Sunflower		4756

53	LD2		69	C	Y	Soybean		3509
54	Potato							
55	DF4	49	70	D	Y			3841
56	YN10		72	D	Y			6645
57	DF4	26	61	D	Y			5310
59	DF4	48	61	C	N			5914
60	HD	44	55	D	N			5522
61	HD	33	63	D	Y			5797
62	HD4	33	62	C	Y	Soybean Sunflower		3086
63	DF4	37	60	C	Y			4210
64	HD4	30	82	D	Y			5273
65	HD4	37	71	C	N			5394
66	LD	36	73	D	Y			4095
67	HD	48	64	D	N			5910
68	HD	38	100	C	N	Soybean		3373
69	HD	46	70	D	Y		Y	5731
70	QHD	44	74	D	Y			3951
71	Waste land							
72	DF4	39	72	C	N	Soybean		2974
F2-1	LD	44		No row				4111
F2-2	HD	51	72	SC	Y			6175
F2-3	HD	38	68	C	Y			5128
F3-1	DF4	56	71	C	Y			3448
F3-2	HD4	28	80	D	Y	Soybean		5859
F3-3	YD	52	55	C	N			6470
F4-1	Q3	38	81	D	Y			3137
F4-2	DF4	48	69	C	Y			4315
F4-3	DF4	48	73	D	Y		Y	2989
F4-4	HD	51	58	D	Y			6229
F7-1	HD	42	55	C	Y	Frenchbean		6609
F7-2	HD4	52	51	D	N			5333
F7-3	HD4	31	52	D	Y			7568
F9-1	Tobacco							
F9-2	LD	35	60	D	Y			6920
F9-3	Tobacco							
F10-1	DF4	30	71					
F10-2	DF4	40	43	C	Y			8444
F10-3	Tobacco	60	95					
F11-1	DF4	38	70	D	Y		Y	5829
F11-2	Tobacco							
F11-3	Tobacco							
F12-1	DF4	46	70	C		Chestnut		6133
F12-2	Tobacco							
F12-3	-	45	52	C	N	Chestnut		6889
F8-1	DF4	39	54	C	Y			3979
F8-2	DF4	57	62	C	N			2140
F8-3	DF4	44	63	C	N			3419

Appendix 8. Field measurements of maize yield in 2001.

Plot No.	Maize cultivar	Plant space (cm)	Row space (cm)	Planting direction	Double row	Inter crop	Polythene mulch	Grain yield at 13% moisture (kg/ha)
1	Vegetable							
2					Y			
3	Tobacco						Y	
4	DF4	37	85	C	Y	Soybean		
5	HD	36	55	C	N			5729
6	HD	34	53	F	Y			
7	HD	39	93	D	N			3998
8	HD	34	73	D	Y			4500
9		37	61	C	N			5490
10	DF4	42	70	D	Y	Soybean		1555
11	HD	39	58	D	Y			6152
12	DF4	37	63	D	Y		Y	4103
13	DF4	37	85	C	Y			3938
14								
15	DF4	41	105	C	N			4133
16	DF4	38	70	D	Y			4862
17	DF4	34	56	D	Y			3500
18	Q3	34	51	D	Y			6061
19	Old	42	58		Y			
20	DF4	39	50		N			
21	DF4	39	63	D	Y			5150
22	HD	38	86	D	Y			4138
23	HD	34	84	D	Y			4077
24	DF4	31	90	C	N			5198
25	DF4	32	92	T	N			4452
26	HD	35	73	C	Y			4074
27	Chili							
28	HD	33	90	C	Y			2828
29	DF4	35	46	C	Y			4535
30	Buckwheat							
31	DF4	47	65	D	N			5150
32	HD	41	51	C	Y			6385
33	DF4	37	85	D	Y	Yam		3936
34	DF4	38	65	D	N			4341
35	DF4				N			3815
36	HD	40	74	C	Y			3952
37		38	38	C	N			
38	DF4	40	88	C	Y			4419
39		34	63	C	Y	Pumpkin		4727
40	DF4	40	70	C	N			5143
41	DF4	33	56	C	Y			3203
42	DF4	34	62	C	Y			5938
43	DF4	43	70	C	N			5581
44	DF4	34	75	F	N			6884
45	DF4	51	80	C	Y	Sunflower		1763
46	HD	34	63	D	Y		Y	5639
47	DF4	36	49	C	Y			1361
48	Wasteland							
49	HD	39	55	F	N			
50	DF4	50	58	D	N			9293
51		40	40	C	N			
52	HD	37	73	D	Y			4779
53	DF4	41	55	C	Y			

54	HD	40		C	Y		Y	4752
55		38	59	C	Y			4140
56		40	55	D	Y			5146
57	DF4	39	68	C	Y			5581
59	HD	56	53	D	Y			5634
60	HD	45	50	C	N			4000
61	DF4	48	59	D	Y			3695
62		38	76	D	Y			2092
63	DF4	39	60	C	Y			3448
64	HD	49	53	D	Y			4721
65	DF4	36	70	C	N		Y	3880
66	DF4	41	75	C	Y			909
67	DF4	38	53	C	Y			5953
68	HD	37	68	C	N			4135
69	HD	43	69	D	Y		Y	2752
70	Q3	44	103	D	Y			5806
71	Wasteland							
72		33	70	D	Y			2417
F1-1								
F1-2								
F2-1	DF4	36	74	C	Y			1703
F2-2	DF4	39	58	D	Y			4935
F2-3	DF4	35	62	D	Y			6794
F3-1	HD	48	69	C	Y			
F3-2								
F3-3		42	61	C	N			2811
F4-1	DF4	46	60	D	Y		Y	2061
F4-2	DF4	46	74	D	Y			5464
F4-3	DF4	43	53	C	N			1568
F4-4	HD	48	50	D	Y			5419
F7-1	DF4	49	63	D	Y			6334
F7-2	DF4	43	56	D	Y			6122
F7-3	DF4	33	58	D	Y			6137
F9-1		43	73	C	Y			3250
F9-2	DF4	43	63	C	N			3889
F9-3	DF4	48	71	C	Y			5680
F10-1	DF4	37	71		Y			
F10-2		34	65		Y			
F10-3								
F11-1		38	65	D	Y		Y	4598
F11-2	DF4	40	56	D	Y			5543
F11-3		49	71	C	Y		Y	
F12-1		36	47	C	N			4435
F12-2		35	60	D	Y			
F12-3		51	76	C	Y	Soybean		3886
F8-1	DF4	47	73	C	Y			3133
F8-2		33	80	C	Y	Soybean		4571
F8-3		31	71	C	Y			3017

Appendix 9. Field measurements of maize yield in 2002.

Plot No.	Maize Cultivar	Planting direction	Polythene mulch	Intercrop	Double/ single row	Row space (cm)	Plant space (cm)	Grain yield at 13% moisture (kg/ha)
1	Q3	D			S	42.5	42.5	5978
2	HD4	C	P		D	70	27.7	6325
3	DF4	C	P		D	57.5	39	3614
4	DF4	C	P	Frenchbean	D	65	43	6352
5	DF4	C			D	60	43	6225
6	DF4	C	P		D	61.75	38.5	5198
7	DF4	C	P	Frenchbean	D	80	33	6464
8	DF4	C	P		S	75	37.5	8114
9	HD4	C	P		S	65	41	6919
10	HD4	C	P		D	62.5	36	6846
11	HD4	C	P		D	60	34	6864
12	HD4	C	P	Soybean	D	67.5	44	5954
13	HD4	C	P		D	58.5	48	3942
14	HD4	C		Soybean	D	66	49	6393
15	HD4	C	P		D	51.25	40	0
16	HD4	C	P		D	50	50	6597
17	HD4	C	P	Frenchbean	D	70	37	7783
18	HD4	C	P		D	67.5	40	8386
19	DF4	C			S	75	42.5	5556
20	DF4	C	P		D	42.5	30	6109
21	DF4	C	P	Sunflower	D	62.5	48	6751
22	DF4	C	P	Frenchbean	D	78.75	36	9239
23	DF4	C	P	Frenchbean	D	80	39.5	5085
24	DF4	C	P	Frenchbean	D	75	39.6	4556
25	DF4	C	P		S	95	49	7289
26	DF4	C	P		D	66.25	37.5	7998
27	DF4	C	P		D	60	39.5	6802
28	DF4	C	P	Frenchbean	D	73.75	44.5	4973
29	DF4	C	P		D	67.25	45	7394
30	DF4	C	P		D	67.5	49.5	5963
31	DF4	C	P		D	66.25	27	7955
32	DF4	C	P		D	60	40	5808
33	DF4	C	P		D	60	34.5	6086
34	DF4	C	P		D	47.5	47	5882
35	DF4	C	P		D	72.5	39.5	5213
36	DF4	C	P		D	75	40	5544
37	DF4	C	P	Frenchbean	D	70	38	5145
38	DF4	C	P		S	75	28	3904
39	DF4	C	P	Frenchbean	D	70	41	6415
40	DF4	C	P		S	100	32.5	6411
41	DF4	C	P		S	80	43	4810
42	DF4	C	P	Frenchbean	D	72.5	37	7864
43	DF4	C	P		D	65	43.5	7924
44	DF4	C	P		S	80	37	7923
45	DF4	C	P		D	70	40	5953
46	HD4	C	P		D	65	42	6750
47	DF4	C		Frenchbean	D	62.5	37	4247
48						0		

49	DF4	C			D	55	36.2	7181
50	DF4	C	P		D	57.5	38.5	10547
51	DF4	C	P		D	52	40.5	3511
52	DF4	C			D	60	44.6	6182
53	DF4	C	P		D	65	34.5	5942
54	DF4	C	P		D	62	48	5633
55	DF4	C	P		D	63.75	35.4	9636
56	DF4	C	P		D	68.75	39.6	9979
57	DF4	C	P		D	67.5	44.5	7018
59	DF4	C			D	75.75	40	5499
60	DF4	C			D	62.5	42.5	3658
61	DF4	C			D	55	33	3644
62	DF4	C	P		D	57.5	35	4914
63	HD4	C	P	Soybean	D	52.5	34	5289
64	HD4	C			D	62.5	50	6240
65	HD4	C	P		S	65	39.5	3683
66	HD4	C	P		D	77.5	41	5281
67	HD4	C			D	66.25	44	4959
68	HD4	C			D	57.5	37.3	5388
69	HD4	C	P		D	57.5	39	5465
70	HD4	C	P		D	60	31	6681
71						0		
72	HD4	C	P		D	60	37	4926
F2-1	HD4	C	P		D	65	33.5	7460
F2-2	HD4	C	P		D	65	36	5516
F2-3	HD4	C	P		D	65	45.5	4902
F3-1	HD4	C	P		D	60	43.5	5855
F3-2	HD4	C		Sunflower	D	60	31	4775
F3-3	HD4	C	P		S	75	34	5911
F4-1	HD4	C	P	Frenchbean	D	80	39	4516
F4-2	HD4	C	P		D	71	39	6229
F4-3	HD4	C	P		D	61	38.4	4167
F4-4	HD4	C			D	60	47	5689
F7-1	DF4	C			D	75	47	6535
F7-2	DF4	C	P		D	57.5	37	7149
F7-3	DF4	C	P	Soybean	D	18.25	41.5	6355
F8-1	DF4	C	P		D	57.5	35	7212
F8-2	DF4	C	P		D	55	35.2	8291
F8-3	DF4	C	P		D	65	41.1	7320
F9-1	DF4	C	P	Frenchbean	D	83.75	41.5	4717
F9-2	DF4	C	P	Frenchbean	D	63.75	54	4477
F9-3	DF4	C	P		D	65	42	6745
F10-1	HD4	C			D	77.5	42	4629
F10-2	DF4	C	P		D	56.25	40	4485
F10-3	HD4	C	P		D	66.25	44	7841
F11-1	DF4	C	P		D	63.75	53	6717
F11-2	DF4	C	P		D	67.5	50	4559
F11-3	DF4	C	P		D	57.5	37.5	6518
F12-1	DF4	C	P		S	75	39	6197
F12-2	DF4	C	P		D	68.75	39	8170
F12-3	DF4	C	P		D	62.5	32	8168

Appendix 10. Farmers' survey of maize cultivation information in 2001.

Plot No	Previous crop	Sowing date	Maize cultivar	Planting direction	Polythene mulch	Manure (kg/ha)	Urea (kg/ha)	Compund (kg/ha)	Phosphate (kg/ha)	Irrigation	Labour (man-day/ha)	Yield (kg/ha)
1	vegetable	03-May	DF4	C	N	7500	1500	0	0	N	450	6000
2	wheat	07-May	QD	C	N	7500	2250	0	0	N	450	5250
3	*	*	*	*	*	*	*	*	*	*	*	*
4	pea	05-May	DF4	C	N	7500	1500	0	0	N	450	4500
5	pea	04-May	DH4	C	N	0	1200	0	600	N	300	4500
6	pea	07-May	JD	C	N	0	1200	150	150	N	210	2400
7	wheat	28-Apr	DF4	C	N	7500	600	0	0	N	180	4500
8	pea	01-Jan	DF4	C	N	0	750	375	0	N	263	5625
9	pea	06-May	DF4	C	N	0	1500	0	900	N	300	2700
10	pea	06-May	DF4	C	N	7500	750	0	0	N	300	3750
11	pea	30-Apr	DF4	C	N	8750	1000	0	0	N	175	5000
12	*	*	*	*	*	*	*	*	*	*	*	*
13	pea	01-May	DF4	C	N	7500	1000	0	0	N	225	3000
14	pea	03-May	DF4	C	N	11250	1125	375	0	N	375	3750
15	pea	01-May	HD4	C	N	0	1000	0	0	N	300	5000
16	pea	06-May	DF4	C	N	8333	1333	0	0	N	200	2500
17	pea	08-May	HD4	C	N	0	600	150	0	N	180	2250
18	pea	09-May	DF4	C	N	0	600	375	0	N	300	3000
19	pea	11-May	DF4	C	N	6000	3000	500	0	N	450	6000
20	pea	26-Apr	DF4	C	N	7500	1500	0	0	N	300	4500
21	pea	06-May	DF4	C	N	15000	1950	0	0	N	300	3000
22	wheat	16-May	HD4	C	N	10714	429	0	429	N	321	4929
23	wheat	16-May	HD4	C	N	10714	1286	0	429	N	321	4714
24	pea	09-May	DF4	C	N	18750	750	375	0	N	275	3750
25	pea	09-May	DF4	C	N	22500	900	300	0	N	300	3750
26	pea	05-May	HD4	C	N	0	1500	0	750	N	375	4500
27	pea	06-May	HD4	C	N	0	1500	750	0	N	375	4500
28	pea	06-May	HD4	C	N	0	1500	0	750	N	300	5250
29	pea	10-May	DF4	C	N	5625	750	563	0	N	300	3750
30	*	*	*	*	*	*	*	*	*	*	*	*
31	wheat	05-May	DF4	C	N	0	750	750	0	N	250	3000
32	wheat	04-May	DF4	C	N	10000	800	0	0	N	200	2500
33	wheat	03-May	DF4	C	Y	13000	400	0	300	N	180	4000
34	wheat	05-May	DF4	C	N	0	900	900	0	N	300	3000
35	fallow	10-May	HD4	C	N	0	1500	0	0	N	300	3000
36	fallow	10-May	HD4	C	N	0	1000	0	0	N	300	3000
37	wheat	12-May	HD4	C	N	0	600	375	0	N	195	2700
38	wheat	10-May	DF4	C	N	0	1238	0	0	N	300	3000
39	wheat	05-May	DF4	C	N	7500	900	0	0	N	300	3000
40	*	04-May	DF4	C	N	9375	1088	0	281	N	300	5250
41	wheat	02-May	HD4	C	N	15000	1500	0	0	N	300	2250
42	wheat	06-May	DF4	C	N	1500	625	0	0	N	125	5000
43	wheat	10-May	DF4	C	N	15000	1238	0	0	N	300	3750
44	wheat	12-May	DF4	D	N	9000	300	0	0	Y	90	3300
45	wheat	02-May	HD4	C	N	15000	1000	0	0	N	300	2500
46	pea	07-May	DF4	C	N	6000	1500	0	750	N	375	4500
47	fallow	14-May	DF4	D	N	5000	300	0	0	N	88	4000
48	*	*	*	*	*	*	*	*	*	*	*	*

49	wheat	08-May	DF4	D	N	7500	750	375	0	N	225	6000
50	pea	26-Apr	DF4	C	N	7500	1500	0	0	N	300	6000
51	pea	26-Apr	DF4	C	N	7500	1500	0	0	N	300	6750
52	pea	12-May	DF4	C	Y	7500	750	0	938	N	263	3750
53	pea	07-May	DF4	C	N	0	938	0	0	N	375	3000
54	pea	04-May	QD	C	N	6000	1125	300	0	N	300	6750
55	pea	08-May	JD	C	N	18750	1500	750	0	N	300	3000
56	pea	03-May	JD	C	Y	5000	1000	250	0	N	200	4500
57	wheat	05-May	DF4	C	N	6000	1125	1125	0	N	300	6000
59	pea	15-May	HD4	C	N	4000	1000	0	0	N	300	5500
60	pea	15-May	HD4	C	N	4500	1125	0	0	N	263	5250
61	pea	08-May	HD4	C	N	10000	1000	0	0	N	200	3000
62	pea	06-May	JD	C	N	7500	1000	0	0	N	400	4000
63	pea	07-May	DF4	C	N	12500	1000	500	0	N	250	3500
64	pea	10-Apr	HD4	C	N	15000	500	250	375	Y	200	6250
65	pea	06-May	DF4	C	N	0	2250	0	0	N	300	4500
66	pea	29-Apr	DF4	C	N	0	1200	0	0	N	300	3000
67	pea	12-May	HD4	C	N	0	1500	0	1500	N	300	3000
68	pea	13-May	HD4	D	N	0	750	0	0	N	250	5000
69	pea	12-May	DF4	D	N	15000	2250	0	0	N	450	3000
70	pea	13-Apr	HD4	C	N	2250	750	0	0	N	150	1500
71	pea	08-May	DF4	C	N	0	600	300	0	N	360	3600
72	pea	12-May	DF4	C	N	0	750	0	750	N	300	3000
F2-1	fallow	06-May	DF4	C	N	7500	1500	0	0	N	225	3000
F2-2	pea	01-May	DF4	C	N	2813	994	0	0	N	300	15
F2-3	pea	08-May	DF4	C	N	7500	600	113	0	N	120	4500
F3-1	pea	01-May	HD4	C	N	0	225	0	45	N	90	*
F3-2	pea	08-May	DF4	C	N	25000	1500	0	0	N	400	4500
F3-3	pea	08-May	DF4	C	N	0	1500	0	0	N	275	5250
F4-1	pea	07-May	DF4	C	Y	0	938	0	0	N	375	3375
F4-2	pea	01-May	DF4	D	N	0	225	75	0	N	75	5250
F4-3	pea	12-May	DF4	C	Y	0	750	0	0	N	400	7000
F4-4	pea	10-Apr	HD4	C	N	15000	500	250	375	Y	175	6250
F7-1	pea	06-May	DF4	C	N	0	1000	500	0	N	400	5000
F7-2	wheat	08-May	DF4	C	N	7500	750	0	0	N	225	3750
F7-3	pea	05-May	DF4	C	N	0	750	0	0	N	300	4500
F8-1	*	*	*	*	*	*	*	*	*	*	*	*
F8-2	*	*	*	*	*	*	*	*	*	*	*	*
F8-3	*	*	*	*	*	*	*	*	*	*	*	*
F9-1	wheat	05-May	DF4	C	N	7500	600	0	0	N	180	3000
F9-2	pea	06-May	DF4	C	N	12000	1200	0	0	N	360	3000
F9-3	wheat	10-May	DF4	C	N	7500	750	0	0	N	200	4500
F10-1	wheat	25-Apr	DF4	C	N	7500	1500	175	0	N	300	3750
F10-2	pea	10-May	DF4	C	N	15000	1500	0	0	N	300	7000
F10-3	wheat	08-May	HD4	C	N	6000	1500	0	0	N	450	6000
F11-1	pea	02-May	DF4	C	Y	7500	750	225	0	N	206	4688
F11-2	wheat	02-May	DF4	D	N	15000	1500	0	0	N	281	5625
F11-3	pea	12-May	DF4	C	Y	0	900	300	0	N	300	5250
F12-1	pea	08-May	DF4	C	N	0	1800	0	0	N	300	6000
F12-2	pea	08-May	DF4	C	N	9000	750	0	180	N	330	2700
F12-3	pea	30-Apr	DF4	C	N	7500	2000	0	0	N	450	4000

Appendix 11. Farmers' survey of maize cultivation information in 2002.

Plot No.	Sowing date	Previous crop	Previous crop yield (kg/ha)	Maize cultivar	Seed (kg/ha)	Planting direction	Polythene mulch	Manure (kg)	Irrigation	Maize yield (kg/ha)	Urea (kg/ha)	Compund (kg/ha)	Super phosphate (kg/ha)	Man-labor (day/ha)
1	18-May	vegetable	*	DF4	45.0	D	N	100	N	6000	750	0	0	300
2	07-May	wheat	4125	DF4	37.5	C	Y	80	N	8250	600	375	0	225
3	16-May	pea	900	DF4	39.0	C	Y	250	N	6900	600	0	0	180
4	06-May	pea	1650	DF4	40.0	C	Y	150	N	7000	100	500	0	200
5	05-May	pea	1650	DF4	24.0	C	N	350	N	6000	750	300	360	210
6	10-May	pea	1000	DF4	40.0	C	Y	700	N	6000	700	0	0	210
7	15-May	wheat	750	DF4	37.5	C	Y	800	N	6000	600	150	300	210
8	03-May	wheat	1071	DF4	38.6	C	Y	280	N	6000	643	257	0	214
9	11-May	pea	*	HD4	30.0	C	Y	200	N	5400	600	180	0	210
10	02-May	pea	1800	HD4	30.0	C	Y	400	N	5900	500	120	100	210
11	03-May	pea	250	HD4	31.3	C	Y	400	N	5625	625	188	0	213
12	*	*	*	*	*	*	*	*	*	*	*	*	*	*
13	07-May	pea	150	HD4	30.0	C	Y	0	N	5175	600	0	0	180
14	02-May	pea	450	HD4	30.0	C	Y	300	N	5250	450	150	0	210
15	03-May	pea	50	HD4	*	C	Y	1500	N	5500	550	200	0	200
16	02-May	pea	1500	HD4	30.0	C	Y	300	N	5250	600	150	0	210
17	07-May	pea	*	HD4	30.0	C	Y	0	N	5200	600	150	0	190
18	09-May	pea	107.1	HD4	30.0	C	Y	1200	N	5143	514	171	0	193
19	05-May	pea	1800	DF4	39.0	C	Y	250	N	10500	750	0	0	210
20	06-May	pea	*	DF4	45.0	C	Y	50	N	6000	450	300	0	300
21	14-May	pea	150	DF4	37.5	C	Y	1000	N	7500	900	375	0	188
22	14-May	wheat	187.5	DF4	37.5	C	Y	500	N	6000	625	0	313	200
23	14-May	wheat	288.5	DF4	26.5	C	Y	500	N	5769	577	288	0	173
24	16-May	pea	375	DF4	37.5	C	Y	500	N	6000	570	225	0	180
25	16-May	pea	112.5	DF4	37.5	C	Y	1000	N	6000	660	263	0	188
26	05-May	pea	*	DF4	39.0	C	Y	300	N	6600	750	300	450	180
27	05-May	pea	*	DF4	24.0	C	Y	300	N	6900	600	360	300	210
28	05-May	pea	*	DF4	24.0	C	Y	350	N	6900	750	300	300	210
29	07-May	pea	0	DF4	40.0	C	Y	600	N	6000	500	0	500	200
30	14-May	pea	120	DF4	37.5	C	Y	0	N	5250	0	0	0	180
31	15-May	wheat	0	DF4	39.0	C	Y	250	N	6000	600	0	180	150
32	02-May	wheat	750	DF4	37.5	C	Y	500	N	6000	600	150	0	210
33	10-May	wheat	300	DF4	37.5	C	Y	1000	N	5250	300	225	0	188
34	15-May	wheat	0	DF4	37.5	C	Y	500	N	6000	450	0	150	180
35	10-May	pea	300	DF4	37.5	C	Y	400	N	6300	705	300	150	180
36	10-May	pea	300	DF4	37.5	C	Y	400	N	6000	630	300	150	195
37	08-May	wheat	*	DF4	37.5	C	Y	1000	N	6000	1103	150	150	180
38	14-May	wheat	1125	DF4	37.5	C	Y	300	N	7125	750	0	0	225
39	11-May	wheat	*	DF4	40.0	C	Y	150	N	7000	700	0	200	200
40	04-May	wheat	*	DF4	75.0	C	Y	600	N	5250	750	150	225	195
41	12-May	wheat	1500	DF4	37.5	C	Y	500	N	6000	600	150	0	195
42	14-May	wheat	1200	DF4	37.5	C	Y	1000	N	6750	600	75	0	195
43	14-May	pea	*	DF4	38.6	C	Y	300	N	7285	857	0	0	193
44	02-May	wheat	*	DF4	37.5	C	Y	300	Y	7500	563	0	0	188
45	07-May	wheat	2000	DF4	40.0	C	Y	1500	N	6500	600	800	0	190
46	16-May	pea	*	Q3	25.0	C	Y	800	N	4500	600	0	300	210
47	11-May	pea	0	DF4	37.5	C	N	0	N	6000	450	0	0	195
48	*	*	*	*	*	*	*	*	*	*	*	*	*	*

49	05-May	wheat	1125	DF4	37.5	D	N	100	N	7500	600	150	0	225
50	14-May	pea	*	DF4	37.5	C	Y	100	N	6000	600	300	0	225
51	14-May	pea	1125	DF4	37.5	C	Y	160	N	6000	600	225	0	225
52	16-May	pea	200	DF4	38.0	C	N	1200	N	5200	500	200	500	220
53	01-May	pea	*	DF4	37.5	C	Y	160	N	6750	750	225	0	300
54	03-May	fallow	*	DF4	40.0	C	Y	800	N	6100	600	200	0	180
55	05-May	pea	1050	DF4	37.5	C	Y	600	N	6000	600	150	0	195
56	17-May	pea	*	DF4	37.5	C	Y	350	N	6000	600	150	0	180
57	10-May	pea	750	DF4	37.5	C	Y	300	N	7200	600	150	0	180
59	05-May	pea	300	DF4	37.5	C	N	200	N	5250	600	150	0	180
60	05-May	pea	*	DF4	37.5	C	N	200	N	5250	600	225	0	180
61	06-May	pea	450	DF4	30.0	C	Y	800	N	6750	600	150	0	180
62	04-May	pea	300	DF4	37.5	C	Y	0	N	6000	600	150	0	195
63	22-Apr	pea	375	HD4	30.0	C	Y	0	N	5250	548	150	0	210
64	12-May	wheat	857.1	HD4	30.0	C	Y	300	N	5142	643	214	0	193
65	11-May	pea	*	HD4	30.0	C	Y	400	N	4800	450	180	0	210
66	03-May	pea	857.1	HD4	30.0	C	Y	0	N	4500	857	0	0	257
67	14-May	pea	*	HD4	30.0	C	N	0	N	5250	450	150	0	210
68	05-May	pea	*	HD4	30.0	C	Y	200	N	5250	600	150	150	210
69	03-May	pea	450	HD4	30.0	C	Y	300	N	5700	600	150	0	210
70	03-May	pea	300	HD4	30.0	C	Y	0	N	5250	600	225	0	195
71	23-Apr	pea	500	HD4	30.0	C	Y	0	N	5200	400	200	0	180
72	14-May	pea	*	HD4	30.0	C	N	0	N	5250	750	150	0	450
F2-1	07-May	pea	600	HD4	30.0	C	Y	0	N	5400	600	150	120	210
F2-2	10-May	pea	900	HD4	30.0	C	Y	0	N	5250	555	0	150	210
F2-3	07-May	pea	1500	HD4	30.0	C	Y	1200	N	4875	600	135	0	210
F3-1	01-May	pea	600	HD4	30.0	C	Y	0	N	4500	150	75	0	150
F3-2	14-May	pea	750	HD4	30.0	C	Y	200	N	4500	600	360	0	240
F3-3	14-May	pea	1500	HD4	30.0	C	Y	300	N	6000	450	180	0	195
F4-1	07-May	pea	*	HD4	30.0	C	Y	100	N	4875	600	750	0	450
F4-2	01-May	pea	*	HD4	30.0	C	Y	0	N	4650	180	105	0	165
F4-3	01-May	pea	450	HD4	30.0	C	Y	0	N	5250	600	0	150	210
F4-4	12-May	wheat	937.5	HD4	30.0	C	N	300	N	4500	750	188	0	188
F7-1	05-May	pea	500	DF4	37.5	C	N	100	N	5000	500	175	0	175
F7-2	04-May	wheat	750	DF4	39.0	C	Y	250	N	4200	600	240	150	210
F7-3	15-May	pea	1050	DF4	39.0	C	Y	0	N	6000	600	300	0	210
F8-1	04-May	wheat	*	DF4	9.8	C	Y	250	N	1500	0	53	0	45
F8-2	06-May	wheat	480	DF4	39.0	C	Y	200	N	7500	600	240	0	180
F8-3	04-May	wheat	300	DF4	30.0	C	Y	400	N	6300	450	600	0	195
F9-1	10-May	wheat	500	DF4	40.0	C	Y	1000	N	6200	600	300	0	210
F9-2	16-May	pea	*	DF4	37.5	C	Y	500	N	6000	375	225	0	195
F9-3	05-May	wheat	2250	DF4	37.5	C	Y	600	N	6150	300	75	75	188
F10-1	04-May	wheat	900	HD4	39.0	C	N	150	N	5400	600	120	0	180
F10-2	05-May	pea	900	DF4	39.0	C	Y	200	N	8100	600	240	0	180
F10-3	13-May	pea	1000	DF4	40.0	C	Y	100	N	6000	0	0	0	200
F11-1	03-May	fallow	*	DF4	37.5	C	Y	300	N	6000	600	150	0	180
F11-2	02-May	wheat	937.5	DF4	37.5	C	Y	800	N	6000	750	94	0	188
F11-3	16-May	wheat	1500	DF4	37.5	C	Y	400	N	6750	450	180	0	180
F12-1	14-May	wheat	1500	DF4	37.5	C	Y	400	N	6750	450	180	0	180
F12-2	06-May	wheat	*	DF4	37.5	C	Y	300	N	6000	600	0	0	200
F12-3	04-May	pea	450	DF4	37.5	C	Y	600	N	7200	750	300	0	195